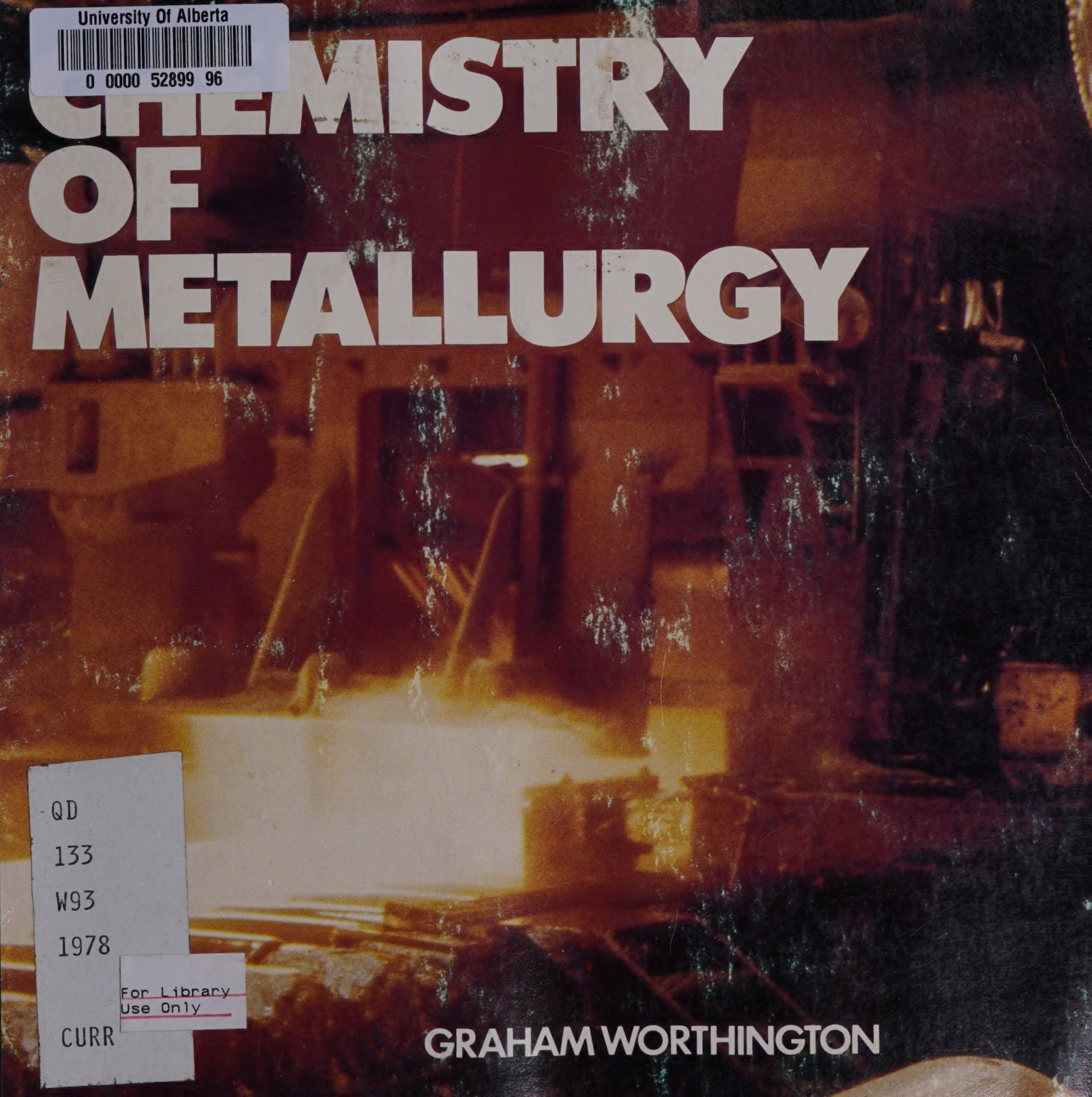
University Of Alberta
0 0000 52899 96

CHEMISTRY OF METALLURGY



QD
133
W93
1978
For Library Use Only
CURR

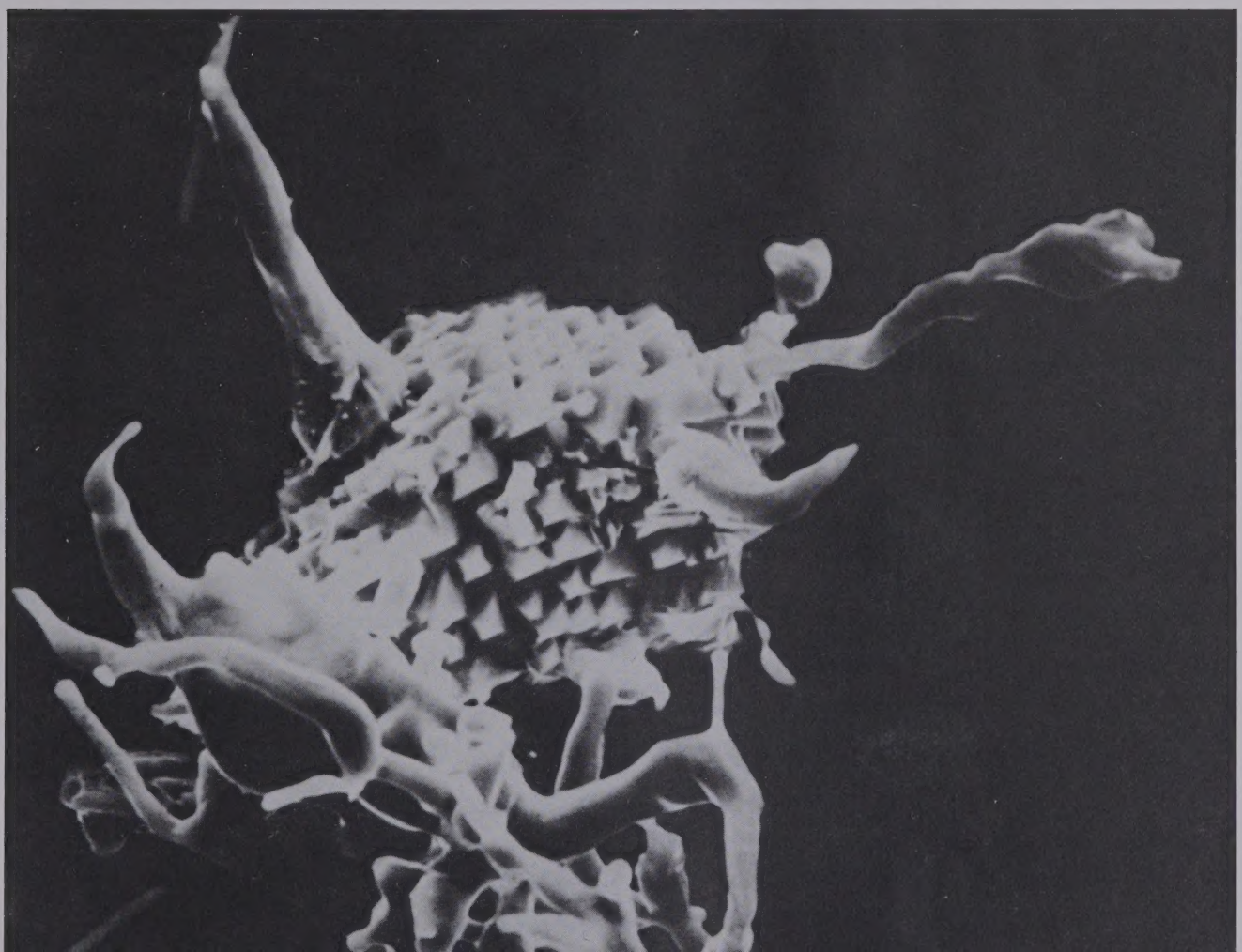
GRAHAM WORTHINGTON

Ex libris
universitatis
albertaensis

CHEMISTRY OF METALLURGY

GRAHAM WORTHINGTON

The Book Society of Canada, Limited
Agincourt, Canada



Copyright © The Book Society of Canada Limited, 1978

It is an infringement of the Copyright Law to reproduce or utilize in any form or by any means, electronic or mechanical, including photocopying, electrostatic copying, electronic recording, or by any information storage, or retrieval system or in any other way passages from this book without the written permission of the publishers.

Canadian Cataloguing in Publication Data

Worthington, Graham, 1942-
Chemistry of metallurgy

(The Action chemistry series)

Bibliography: p.
Includes index.
ISBN 0-7725-2005-4

1. Chemistry, Metallurgic. I. Title.
II. Series.

QD133.W67 546'.3 C77-001688-X

ISBN 0-7725-2005-4

THE ACTION CHEMISTRY SERIES

Core book

Action Chemistry/Ken Ashcroft

Booklets

Chemistry of Man & Molecules/Lou Birenbaum
Chemistry of Photography/Ken Ashcroft
Chemistry of the Car/Ken Ashcroft and Joe Hammill
Water, Chemistry & Ecology/Joe Hammill

The cover of this book shows steel being rolled into long thin coils in a hot strip mill. Several sets of rolls progressively reduce its thickness. The coils then go to the cold reduction mills to be reduced to sizes as thin as 0.15 mm.

The previous page shows iron whiskers which have grown during the reduction of an iron oxide particle containing about 2 per cent calcium oxide.

Artwork/ Frank Zsigo

Printed in Canada by The Bryant Press Limited

1 2 3 4 5 6 7 83 82 81 80 79 78

LIBRARY
UNIVERSITY OF ALBERTA

Contents

Acknowledgments iv

Author's acknowledgments iv

Introduction: Metallurgy in history v

Chapter 1: Extraction and refining 1

Principles of extraction 2
Experiment 1.1 Reduction of an oxide with hydrogen 3
Experiment 1.2 Reduction with carbon 4
Experiment 1.3 Electrolytic refining 4
Specific processes 4
Iron 4
Steel 6
The Bessemer converter 6
The open-hearth furnace 7
The basic oxygen furnace 8
The electric arc furnace 8
Copper 10
Experiment 1.4 The flotation cell 11
Experiment 1.5 Electrolytic refining of copper 13
Nickel 13
Zinc and lead 13
Aluminum 14

Chapter 2: Alloying 16

Experiment 2.1 Comparing a pure metal and an alloy 16
Why do the properties change? 17
Experiment 2.2 Cooling curves for pure and impure substances 19
Experiment 2.3 Plotting a phase diagram for two miscible solids 19
Experiment 2.4 Plotting a phase diagram for two immiscible solids 22
Experiment 2.5 Plotting the most common phase diagram for metals 24
Microstructures 26
Experiment 2.6 The microstructure of lead-tin alloys 26
Steel: the iron-carbon system 27
Experiment 2.7 Microstructures of carbon steels 29

Chapter 3: Treatment and testing 30

Treatment 30
Experiment 3.1 Heat treatment of steel 30
What happens to a metal under stress? 30
Experiment 3.2 The bubble raft 31
How do dislocations alter the properties of a metal? 32
Destructive testing 33
Experiment 3.3 Tensile tests 33

2661163

Non-destructive testing 34
Experiment 3.4 Magnetic dust method 34
Experiment 3.5 Fluorescent test 34
Experiment 3.6 Making a sulphur print 34

Chapter 4: Corrosion 35

Recommended experiments 35
Corrosion in automobiles 35
Corrosion in bridges 36
Protection against corrosion 36

Chapter 5: "Minor" and "modern" metals 39

Titanium 39
Beryllium 40
Palladium and platinum 41
Uranium 41
Whiskers 42
Semi-conductors 42
Other metals 42

Word meanings 43
Reference materials 44
Special materials for experiments 44
SI units conversion chart 45
Index 45

Author's acknowledgments

The author wishes to thank such friends as Fred Oliphant, Joe Hammill and Tom Lowden, without whose help the writing would have been a much more difficult task. Thanks are also due to Ken Ashcroft for his support in all stages of development, to Nancy Oliphant for preparing the typescript, and to John Redman and Norman Holt, the editors.

Acknowledgments

Permission to reproduce illustrations is gratefully acknowledged below. Care has been taken in the preparation of these acknowledgments; the publisher would appreciate being informed of any errors.

Alcan Canada Products Limited 1-13
K. Ashcroft 1-5, 4-1, 5-3
De Havilland Aircraft of Canada Ltd. 5-1
Heinemann Educational Books Ltd. 2-6
INCO Ltd. 1-10, 1-12
McMaster University, Department of Metallurgy and Materials Science title page
National Aeronautics and Space Administration 5-2
Steel Company of Canada Ltd. cover, 2-11, 4-2, 4-3
G. Worthington 2-2

Introduction: Metallurgy in history

The Encyclopedia Britannica defines metallurgy as "the science of extracting metals from their ores, refining, purifying, and working them . . . to adapt them to use." Metallurgy also deals with the structure of metals. It includes, too, a knowledge of the ways in which metals may be mixed with metals or other materials to form alloys, and why these alloys are made.

Perhaps you are rather surprised to find that this whole book deals only with metallurgy. A few minutes thought should help you to see the tremendous importance of metals in your world. Indirectly, therefore, the science of metallurgy is just as important to you as metals themselves. Consider your regular routine from the time you wake up until you get to school. To give you one example: the current that powers your electric alarm clock is carried by copper or aluminum wires. Think of other ways in which metals affect your morning routine. Now extend your thinking beyond this brief part of your day and you will see that metals are necessary to almost the whole technology of modern civilization.

When you hear the words "modern civilization" your first thought is probably of the technology that surrounds us. As you have just seen, metals are a basic part of this modern technology. But people have been working with metals for many thousands of years, and it is this long experience with metalworking that has made possible our modern industrial civilization.

Obviously, people have not always used metals. In a few remote parts of the world today small groups of people still live by hunting and growing food, using little or no metal. Instead, they rely on tools, weapons and utensils of stone, wood and clay. But their physical lives are poor and hard compared to ours.

It was during the Neolithic, or New Stone Age, that people first learned to refine, shape and use metals. This was the period in human culture, perhaps beginning about 10 000 B.C., when some groups had learned to live not only by hunting and gathering, but by growing grain and vegetables, and by raising and herding animals for food. Planting crops, cutting meat and hides, chopping wood and harvesting grain must all have been slow, hard work, even with their carefully made stone tools.

From very early times, of course, people had known of a few metals and had realized that they were different from rock, wood or clay. Gold and silver can be found in a nearly pure form in the sands and gravels of a few stream beds. In some rare places where a meteorite had crashed to earth, copper may have been found in its native state. Some early peoples learned that they could work this copper by beating and pounding it free from its surrounding rock and then hammering it into ornaments. Gold and silver, of course, were highly valued for the same purpose because of their colour and lustre.

A real break-through came when some genius, probably about 3500 B.C., learned to smelt copper, that is, to melt the copper out of the other

materials in the rocky ore. Malachite, the most common ore of copper, is a distinctive blue-green colour. Other ores of the same metal are also bright or eye-catching colours. Perhaps someone, attracted by the colour, deliberately put some of the ore in a camp-fire or pottery kiln. It was an important discovery that, when red-hot, the copper would melt and run out of the rock. Once the metal cooled, it became solid again. By heating and hammering it, a chunk of the metal could be beaten into the desired shape. Copper, of course, is a comparatively soft metal, but hammering its edges will harden and sharpen them. A second break-through came when it was found that some ores contain tin. When these ores were heated, and the melted tin and copper mixed, a much harder and more useful metal was formed. We call this mixture, or alloy, bronze.

The hardness of bronze, and the sharp edge it will take and hold, made it a far more useful metal than earlier materials for tools, weapons, household utensils and for sculpture. Metal tools made a huge number of tasks easier – farming, forestry, building, and so forth. More food could be grown more easily; this freed more people to live in cities, rather than in small villages. Specialist groups developed – not just metal-smiths, but kings, traders, craftsmen. Probably because there was enough extra food for the members of the ruling class and their servants, and because there was a need to keep records of food, clothing and utensils paid to the palace, systems of writing were developed. This city life, with its permanent government and temples, its class structure, crafts, trade and commerce, is known as civilization. By about 3000 B.C. civilization had developed or was beginning in several parts of the world, including the valleys of the Nile and the Tigris and Euphrates.

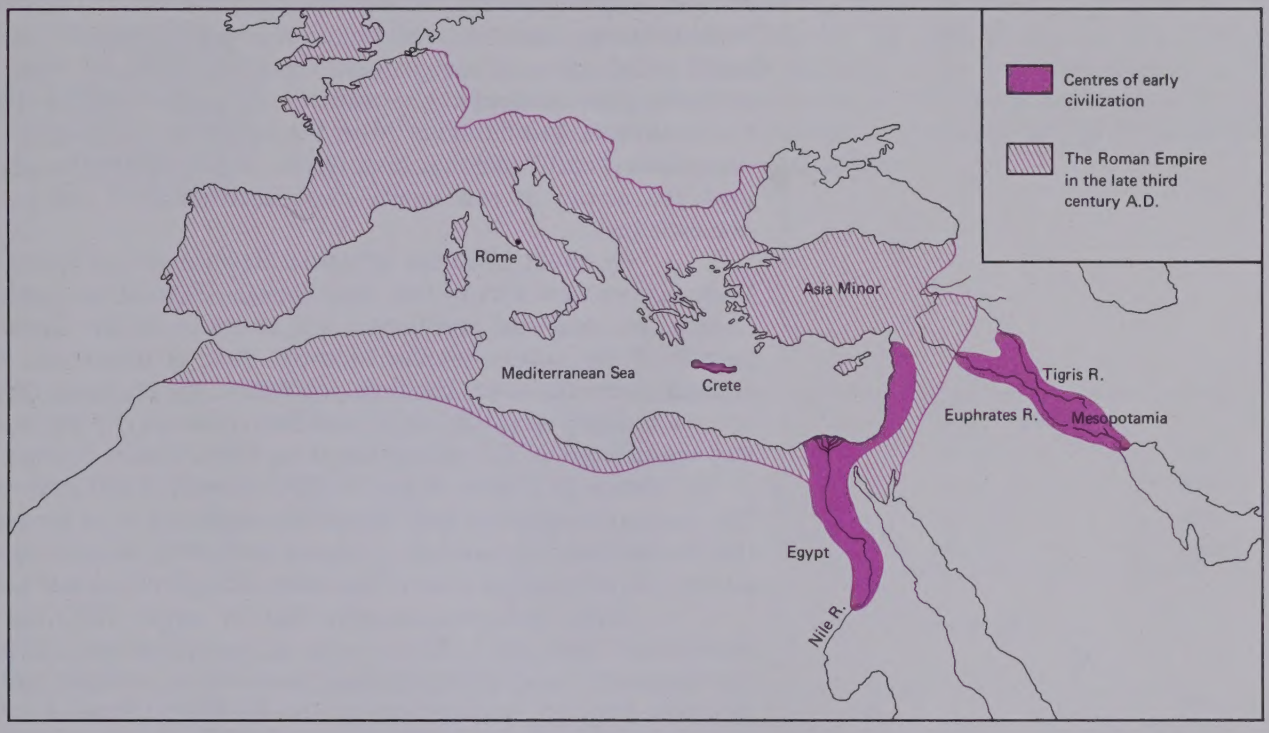
By as early as 1200 B.C. in Asia Minor, people had learned to extract iron from its ore. This was a more difficult process than the making of bronze. Even using charcoal fires and bellows, smiths could not heat the ore sufficiently to melt the iron. Instead, they had to heat the ore in a bed of charcoal until they had turned it into a hot, spongy mass. By beating the spongy ore they could drive the blobs of soft iron out of the slag. These chunks or balls of iron could then be reheated and hammered into shape. Iron tools and weapons were not in themselves superior to bronze – they certainly did not have the qualities of modern steel. The great advantage of using iron was that this metal was far more plentiful than tin. Knowledge of iron working had spread to parts of Europe by about 1000 B.C. There, too, iron deposits were fairly common. Tools and weapons became cheaper and more commonly used. This development helped to spread civilization around the shores of the Mediterranean Sea.

By the time of the Roman Empire several metals were known and were widely used. Gold, silver and bronze were used for jewelry, coins, ornaments, statues and tableware. A very wide range of tools, utensils and weapons was made from bronze and iron. Mercury had been discovered, and was used in the extraction of gold and silver from their ores. Zinc alloyed with copper produced brass, which was used for household wares and for coins of small denomination. In the streets and in the wealthier homes of Roman cities, lead was used for water pipes. The Romans made few metallurgical discoveries, but under their

empire metals were produced and distributed on a wide scale. The use of cheap metals spread throughout the empire and even beyond its borders.

In the fifth century A.D. the Roman Empire in the West collapsed. Its fall was accompanied by great social changes. Invaders, mostly Germanic tribes, pushed their way into the empire and settled. Governments and standing armies and the civil service disappeared or shrank almost to nothing. Many cities were nearly or completely deserted. Trade declined, and much of Europe fell back to an economy of small villages, each having to be nearly self-sufficient for food, clothing and tools. The production of metals declined sharply.

Early civilizations in the Mediterranean area



After about 1000 A.D. conditions in Europe began to improve. The devastating raids by Vikings, Magyars and Moors had been stopped. Towns began to grow again, new land was cleared for farming as the population increased and trade revived. The production of metals rose to meet an increasing need. Eventually the metal-workers of the Later Middle Ages were to develop techniques better than those used in Roman times. A part of this new knowledge was discovered by the alchemists, who for hundreds of years tried by their experiments to extract gold from base metals or to change base metals into gold. They failed, of course, but by trying they developed techniques such as distillation. They also discovered new elements such as arsenic, bismuth, antimony and phosphorus.

During the Middle Ages there was a constant demand for large cast bells for Europe's thousands of churches and cathedrals. This demand pushed

metal-workers to expand their knowledge. In the fourteenth century, the Catalans in Spain developed a new type of forge which made it possible to produce in a single heating several tonnes of wrought iron. In the same century, German metal-workers developed a small forerunner of today's blast furnace, from which several tonnes of cast iron could be poured from a single loading. From the fourteenth century gunpowder was used more and more. This meant a demand for big cast iron or bronze cannon, huge numbers of cannon balls and small arms.

In the sixteenth and seventeenth centuries Europeans sailed out to discover, explore and exploit other parts of the world. The wealth that flowed back to Europe made its economy grow even more quickly, and led to more demand for all types of metal wares. Great quantities of wood were needed to make the charcoal needed to smelt iron. In England, by the eighteenth century, a crucial shortage of timber led to the invention of a method of smelting iron using coke – coal which has been heated to red heat in the absence of air. England had plenty of coal in well-established mines; it had long been used for domestic fuel.

By about 1780 the Industrial Revolution was under way in England. Many factors were part of this great change. Three of the most obvious were increased iron and coal production, the invention of the steam engine and the growth of the cotton textiles industry. Just as important, perhaps, but less dramatic, were the swift growth in population, the increased production of food, and the building of roads, canals, and later, railways. To give one example of the way industry grew, the production of pig (cast) iron in England rose from about 27 000 tonnes in 1760 to about 900 000 tonnes in 1800 (and went on growing). The production of more iron cannot be considered to be the cause of the Industrial Revolution, but you can probably see how a plentiful supply of iron supported, and encouraged most of the other changes mentioned above.

Many historians consider that by about 1860 the "first Industrial Revolution" had ended. To our eyes, of course, the ways of 1860 seem rather old-fashioned: hoop skirts, top hats, horse-drawn carriages, and so forth. But by that time England, parts of Europe and the United States were well into the era of "modern" technology. They were building factories, mines, railways and steamships. It is the "second Industrial Revolution" which began in the 1870s that has produced most of what we consider to be modern technology: modern medicine, the electronics industry, cars and airplanes.

At the beginning of this chapter you were asked to consider the part that metals play in our lives today. After reading this chapter you can probably work out for yourself how the development of metallurgy up to 1860 is a crucial part of the foundation of the technology the world enjoys today.

1 Extraction and refining

Before metals can be used, they must first be extracted from the earth's crust. Very few metals exist there in their metallic form, but rather as compounds, known as ores. The availability of a metal depends upon how easy it is to extract and refine it, rather than upon its abundance. For instance, aluminum is extracted from bauxite, which is not a rare ore. But the method of refining aluminum is expensive, and this is one of the reasons that aluminum is more costly than steel.

Canada leads the world in mineral exports, and ranks third behind the United States and the Soviet Union in mineral production. In 1976 the value of *metallic* minerals produced in Canada was about $5.2 billion – a third of the value of all mineral production. Almost all the minerals needed in a modern economy can be produced in Canada, although a few, such as manganese, chromium and bauxite are imported from the areas where they can be more cheaply produced. As mines are worked out and new ones discovered and developed the geography of the Canadian mining map changes.

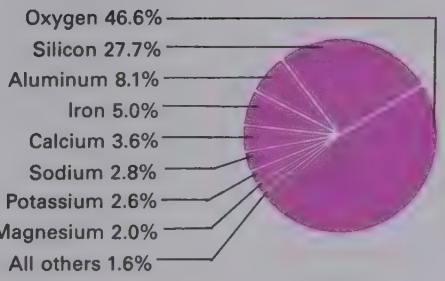
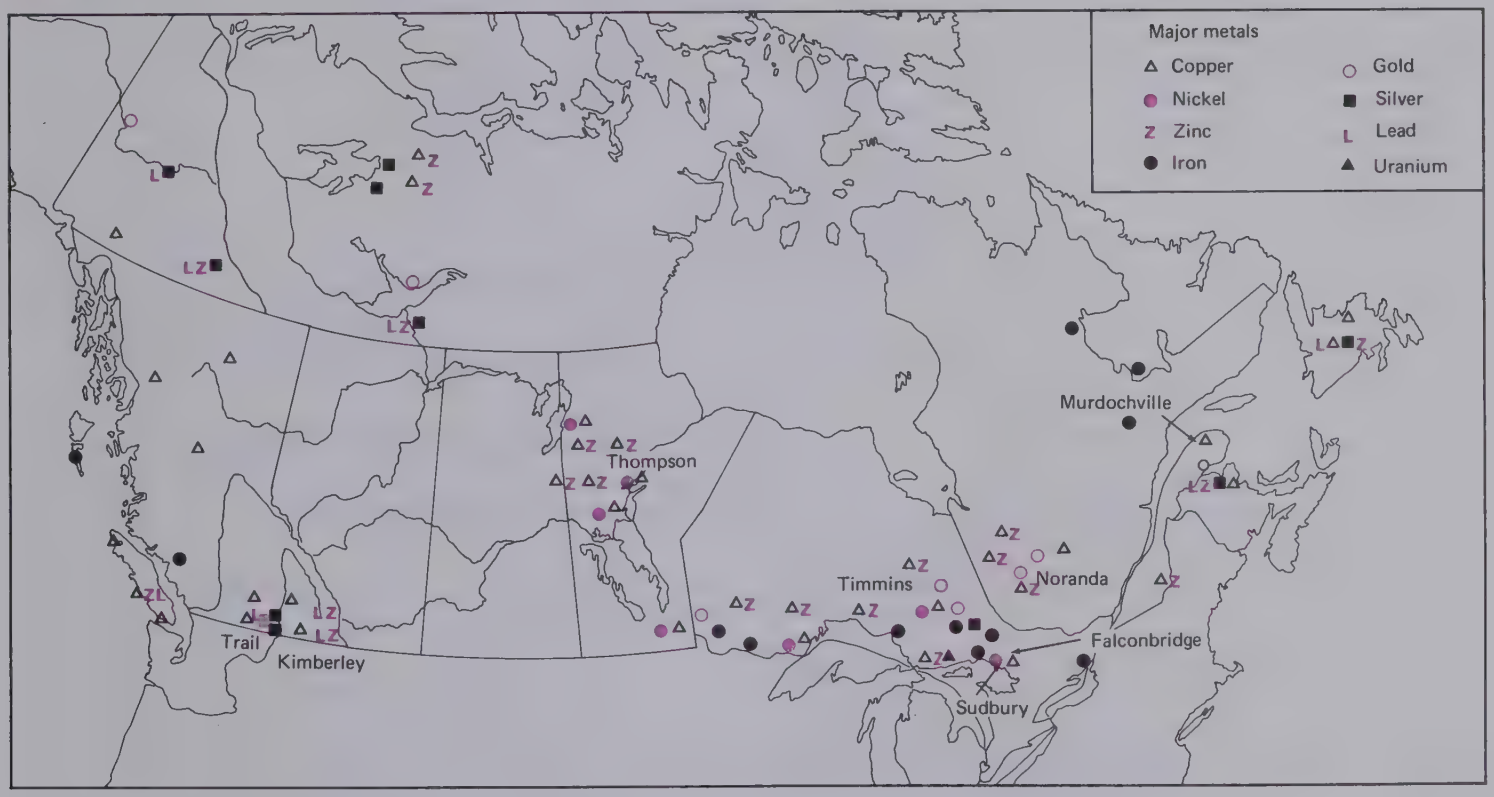


Figure 1-1 Approximate composition of the earth's crust by mass

Figure 1-2



Principles of extraction

The extraction of a metal from its ore is usually a series of chemical reactions. The processes are complex but the basic reactions which follow are simplified so that you can do them in the laboratory.

Basically, the major reaction is one in which the ore is roasted to an oxide and then reduced to the metal.

Another method used either for extraction or for final purification is electrolytic refining.

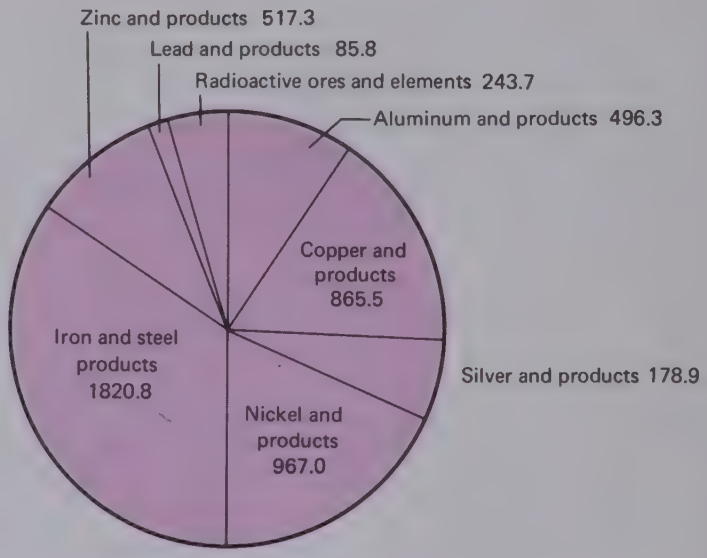

Zinc and products 517.3
Lead and products 85.8
Radioactive ores and elements 243.7
Aluminum and products 496.3
Copper and products 865.5
Iron and steel products 1820.8
Silver and products 178.9
Nickel and products 967.0

Figure 1-3 (a) Canadian exports of metallic minerals and products in 1976 ($ millions)

Source: Canadian Imperial Bank of Commerce: Economics Division

Figure 1-3 (b) Major minerals, value of production, 1964 & 1976 ($ millions)

Source: Statistics Canada, Catalogue 26-202

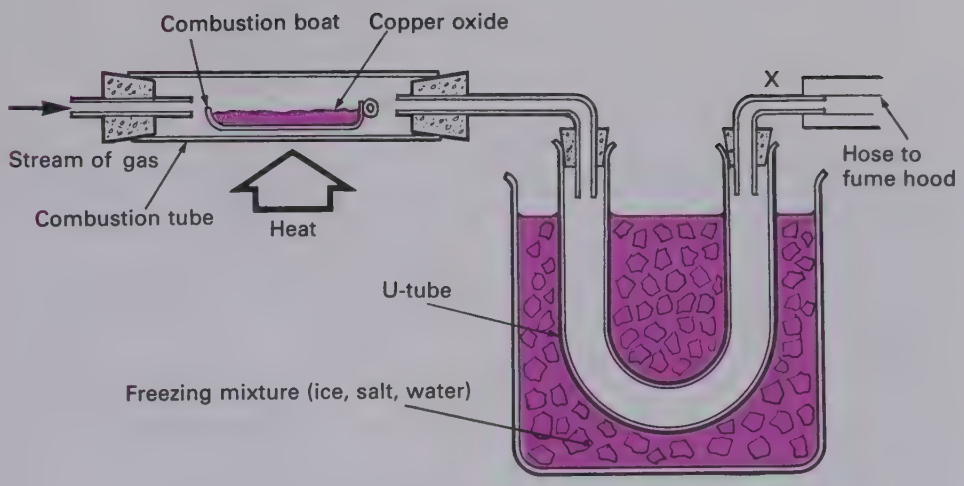


Figure 1-4 Heating copper oxide in a stream of gas

● *Experiment 1.1*
Reduction of an oxide with hydrogen

Your teacher will set up the apparatus shown in Figure 1-4 and will help you to do this experiment.

Pass a stream of gas from the gas supply – mainly methane – through the tube, and heat the material strongly. Caution! You must not turn on the Bunsen until all the air has been displaced from the apparatus by the stream of gas. If the following test is not carried out, the apparatus may explode. Disconnect the hose, and collect a test tube full of the gas coming from tube X. Take it 3 metres away from the apparatus, then test the gas with a burning splint. The sample may explode. Repeat the test until a test tube of gas that burns slowly is collected. It is then safe to turn on the Bunsen burner. (If the Bunsen had been turned on at the stage when the sample exploded, the apparatus would have also blown up.)

Continue heating until no further change occurs in the heated tube, and no more material collects in the U-tube. Allow the apparatus to cool.

Carry out tests to identify the materials in the two tubes. You should then be able to complete the equation below, and write a chemical equation for the reaction.

copper oxide + hydrogen ⟶ [redacted]

Not many metals are extracted from their ores using hydrogen. Why? Perhaps the following will help you to answer.

• *Experiment 1.2*
Reduction with carbon

Make a small hole in a charcoal block using a borer. Fill the hole with lead oxide. Cover the top layer of oxide with a very thin layer of anhydrous sodium carbonate. Now strongly heat the material on the block, using a Bunsen burner and a mouth blowpipe. Your teacher will show you the best way to use the blowpipe.

Continue the heating until you see no further change taking place. Allow the block to cool, and examine the product. You may scrape out the substances to examine them more closely.

What happened to the sodium carbonate? To find out the reason for using sodium carbonate in this way, look up the word *flux*.

Repeat the experiment with other metal oxides. Why do you think the experiment works well with lead oxide, but very poorly with iron oxide?

Soak the blocks in water after you have used them.

Figure 1-5 Reacting lead oxide with carbon

• *Experiment 1.3*
Electrolytic refining

Clean two strips of nickel with emery paper. Place these strips in a beaker containing nickel chloride solution, making sure they do not touch each other. They are the electrodes in the reaction. Connect a 12 volt d.c. supply across them.

How do the electrodes differ after 5 minutes? What is formed? How would this experiment be used on a larger scale in nickel plants in Sudbury, Ontario?

Specific processes

Iron

Hamilton, Ontario, accounts for over half the iron and steel produced in Canada.

Canadian iron ore is mined mainly in Newfoundland, Quebec, Ontario and British Columbia. It is reduced in blast furnaces in Ontario and Nova Scotia. In 1976 iron ore was Canada's most valuable mineral: 55 million tonnes, worth $1.24 billion, was produced.

The basic design of a blast furnace has not altered in many years. The principle is that all the products come out of the furnace as fluids; iron and slag from the bottom in the liquid state, and carbon monoxide and carbon dioxide as gases from the top of the furnace. The furnace can thus run continuously until the lining needs to be replaced. The cooled slag is used as aggregate in construction materials. Heat is conserved by the hot, top gases transferring their heat to the incoming air in a heat exchanger.

The reactions in the blast furnace are complex, since many side-reactions take place. A simplified scheme is:

(a) the limestone decomposes on heating:

$$CaCO_3 \longrightarrow CaO + CO_2$$

(b) the carbon dioxide reacts with the coke:

$$CO_2 + C \longrightarrow 2CO$$

(c) carbon monoxide reduces the iron oxide:

$$Fe_3O_4 + 4CO \longrightarrow 3Fe + 4CO_2$$

(d) calcium oxide combines with impurities to form slag:

$$CaO + SiO_2 \longrightarrow CaSiO_3$$

If, in reaction (c), the oxide of iron used were Fe_2O_3 and not Fe_3O_4, what would the equation be?

Impurities besides silica are taken out in the slag, but their removal is not complete at this stage.

What is wrought iron?

This process produces pig (or cast) iron, which contains many dissolved impurities (up to 3.5 per cent silicon, 0.1 per cent phosphorus, 2 per cent manganese, a few per cent of carbon and up to 0.06 per cent sulphur).

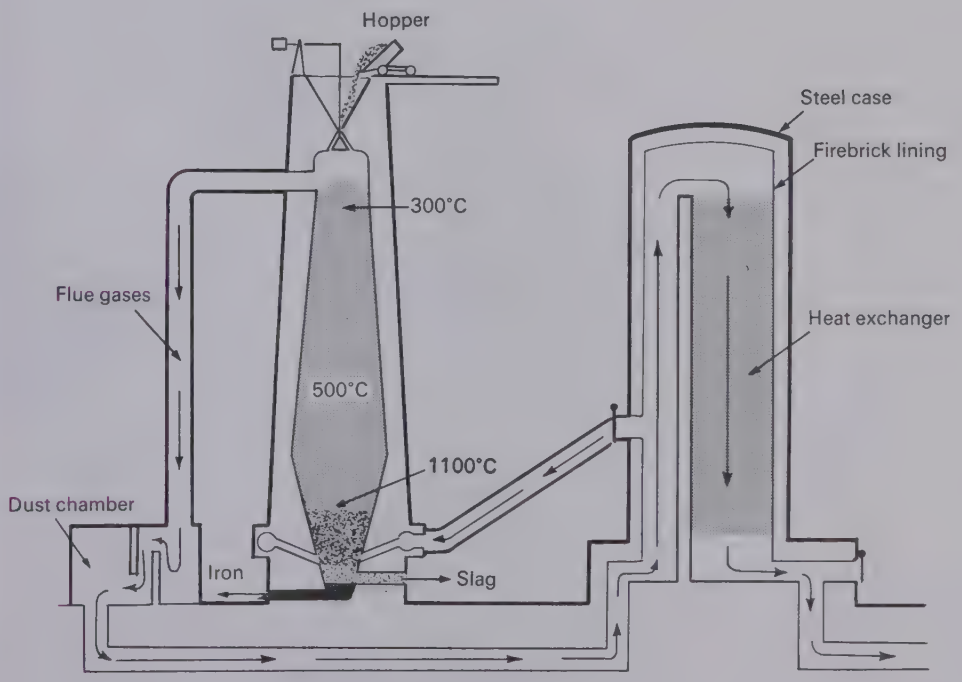


Figure 1-6 Diagram of a blast furnace

Steel

If the impurities are removed from pig iron and less than 2 per cent carbon remains, the product is known as steel. The differences in the carbon content alter the properties of steel, as you will see on page 30.

There are basically four methods of making steel. Three rely on the same chemical reactions.

The Bessemer converter

This process was introduced in 1856 in England by Henry Bessemer. Today, most Bessemer converters have been replaced by newer, more efficient methods of making steel. But at the time of its introduction the converter was tremendously important. For the first time large amounts of steel could be produced quickly and cheaply. The process involves blowing air through molten pig iron to burn away the impurities. The converter can be tilted to make the loading of up to 50 tonnes of pig iron easier. It is then righted for the blowing process.

Some of the iron is oxidized by the oxygen in the air blast.

$$2Fe + O_2 \longrightarrow 2FeO$$

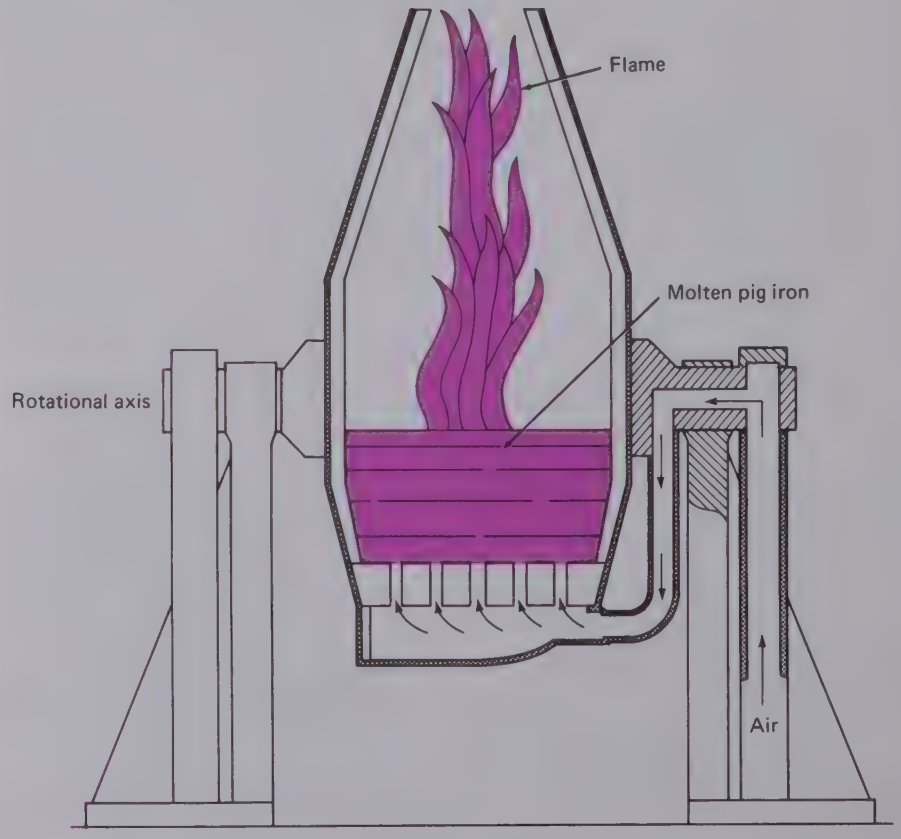


Figure 1-7 The Bessemer converter

The iron oxide is reduced by the impurities to iron.

$$Fe_3O_4 + 4C \longrightarrow 3Fe + 4CO$$

$$Fe_3O_4 + 2Mn \longrightarrow 2MnO_2 + 3Fe$$

The oxides produced form a slag which is separate from the resulting steel, which is poured off. The heat needed for the process comes entirely from the oxidation of the impurities. Only the iron is heated; the air blast is cold.

Find out why this process has become less popular in recent years.

The open-hearth furnace

This is still the most popular method, but it is being replaced by the basic oxygen furnace. The principle is the same as in the Bessemer process except that the heating is done by the burning of a gas or oil flame across the top of the molten pig iron. The heat produced in a Bessemer converter is wasted. The heat produced in the open-hearth process is used to preheat the incoming air.

What are the disadvantages of the open-hearth furnace? Why does a steel company use more than one open-hearth furnace but only one blast furnace?

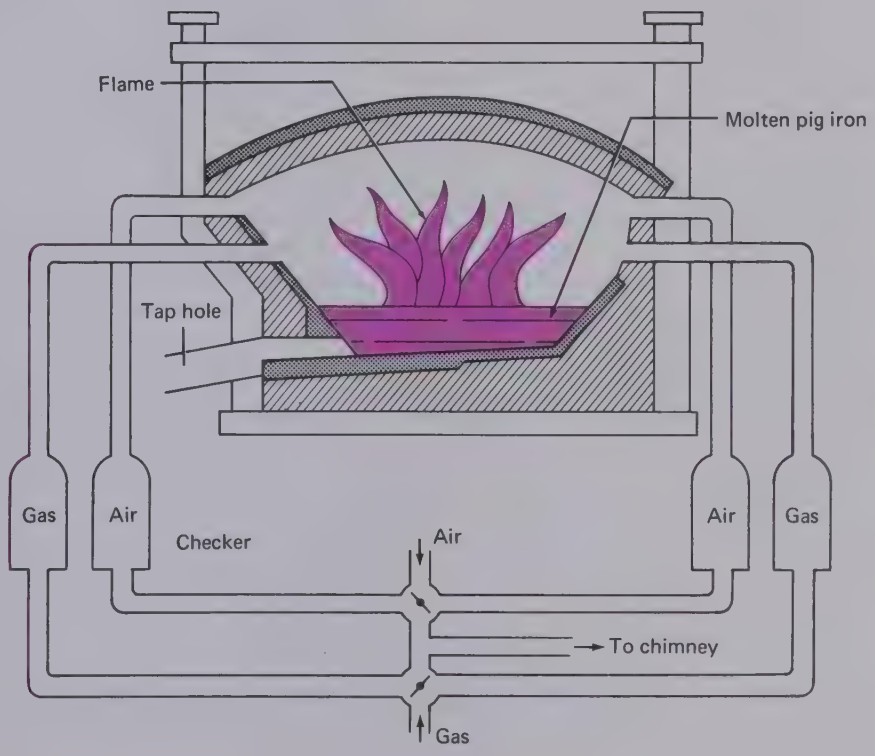


Figure 1-8 The open-hearth furnace

The basic oxygen furnace (BOF)

The demand for increasingly larger amounts of steel led to the design of a new process with greater efficiency, economy and productivity. The BOF was introduced in Austria in 1952 and by the 1960s installations had been made by the thousands.

The shape of the furnace is similar to that of a Bessemer converter, but instead of air blown up from the bottom of the vessel, this furnace uses a water-cooled tube to blow almost-pure oxygen down onto the surface of the metal. Liquid iron from the blast furnace is poured into the crucible and the oxygen lance is lowered in. No fuel is required: the stream of oxygen produces in the molten metal a series of vigorous chemical reactions. Less heat is required because the useless nitrogen present in air is missing. Impurities such as carbon, phosphorus and sulphur are oxidized and boiled off as gases. From 0.1 per cent to 1.5 per cent of carbon remains. To produce a particular grade of steel, other metals such as manganese, chromium, tungsten, nickel and cobalt may be added.

The process is much faster than the open-hearth method. A large open-hearth furnace may produce as much as 590 tonnes in a single heat, but the process may take as long as nine hours. A large basic oxygen furnace today can hold as much as 250 tonnes, but the heat may be completed in less than an hour.

In treating steel after its removal from the furnace, large volumes of water are used for cleaning, lubrication and cooling of the metal. This water picks up oils, acids and metal particles. Simply pumping this water back would result eventually in fouling the source. Filtration equipment to recycle water within the plant is expensive, but in order to reduce damage to the environment operators have no choice but to install such equipment.

The electric arc furnace

The burning of a fuel in a furnace can add to the impurities in the finished product. Where a high-grade steel is required, with or without alloys, the use of such a fuel is undesirable. The electric arc furnace was designed so that the melting and refining could be totally controlled.

Scrap metal is used in the charge and placed on a bed of lime. Most of the silicon, manganese and phosphorus is removed by the slag after the melting and then iron ore is added to remove the carbon and further phosphorus. This slag is raked off and replaced by a layer of lime, fluorspar and carbon. This removes the sulphur.

The steel is then analysed and any required additions are made before the metal is tapped off. Small amounts of other elements are usually added to the steel depending on its proposed use. These elements can be added in all the above processes either during or toward the end of the refining.

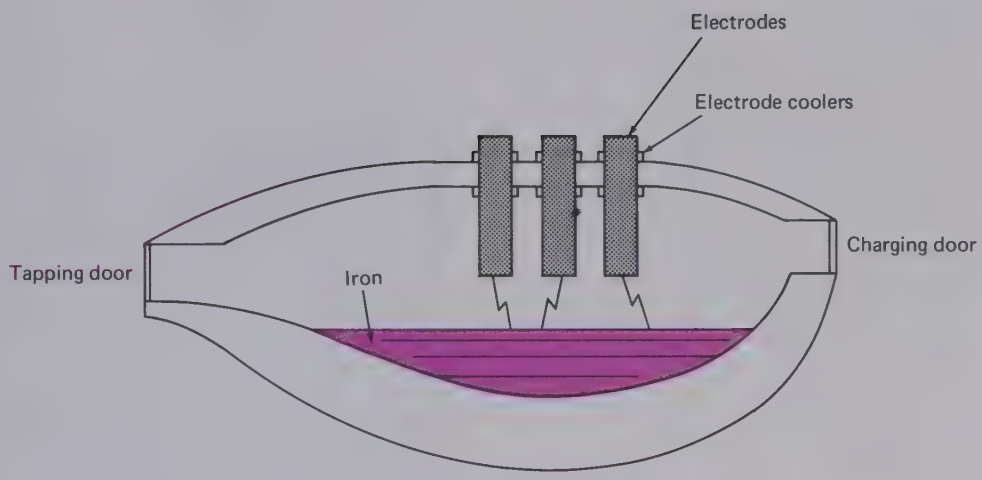


Figure 1-9 The electric arc furnace

Heavy industry has grown in the western provinces in recent years. In northern and central Alberta, for instance, $12 billion worth of industrial expansion is under way. The subsequent increase in housing and high-rise office blocks made the steel industry realize that there are many outlets for their products.

Large orders are due to be placed for the proposed Alaska Highway natural gas pipeline. The Steel Company of Canada's western division, Edmonton Steel Works, produces a range of pipes at its Camrose plant some 80 kilometres south-west of Edmonton. Rods and grinding balls used in the crushing of ore are also produced as well as parts used by the oil industry and agriculture. The two electric furnaces can produce up to 80 tonnes of steel in three hours.

Steel has become such an important metal in our lives that some articles made from it may be seen no matter where you are. It may be adapted by heat treatment or alloy additives to produce a wide range of properties for many uses. Where has steel been used in your school building, in your laboratory and its apparatus, and in your home?

Refer back to Figure 1-3(a). You will see that iron and steel products comprise the largest share of metallic exports by Canada and it is forecast that the known sources of the ore are sufficient for Canada's requirements up to the year 2000.

Copper

Copper, lead, molybdenum and zinc requirements for expected domestic needs and exports can essentially be met until the middle or late 1980's from operating mines and from known but undeveloped mineral deposits considered likely to be brought into production; thereafter, to meet forecast requirements, production will need to be supplemented from other known mineral deposits or from deposits yet to be discovered.

Metal Mining in Canada, 1976-2000

Canada is the fourth largest producer of copper in the world, accounting for 9.8 per cent of worldwide production in 1976. Nine provinces produced nearly 750 000 tonnes valued at $1126 million. The major centres for production are the Sudbury area and Flin Flon in Manitoba. Ores from the Atlantic provinces are processed at Noranda and Murdochville in Quebec.

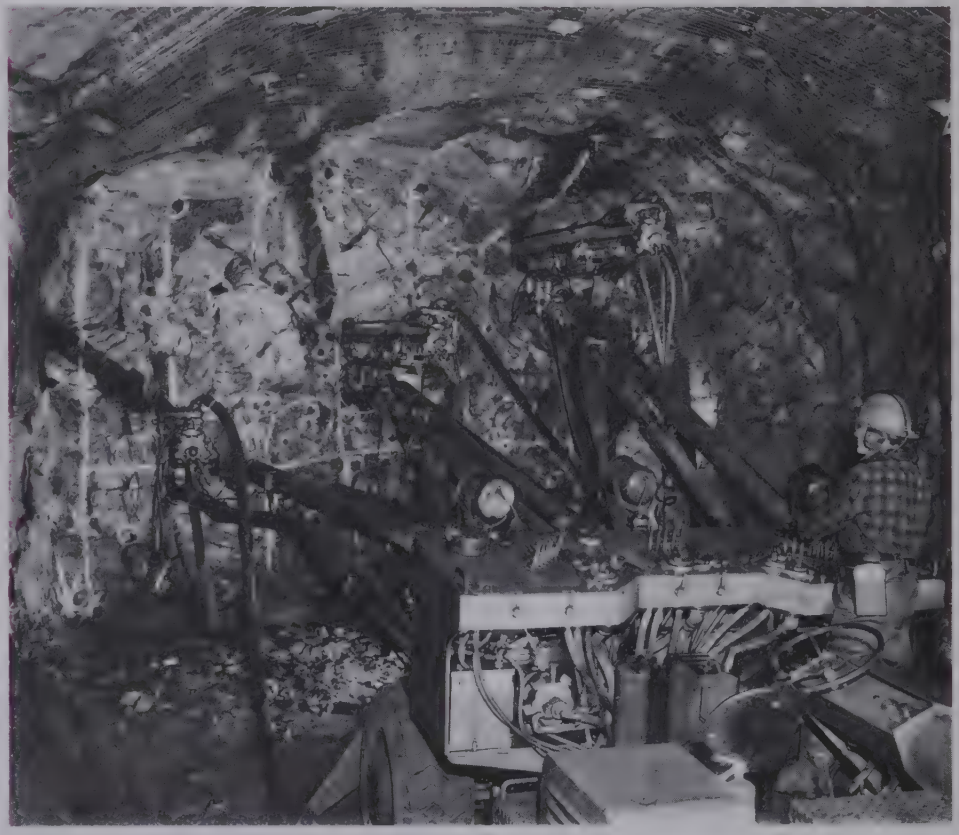


Figure 1-10 Drilling in a Sudbury nickel-copper mine

The main ore is chalcopyrite ($CuFeS_2$) which is usually found in large rocks which contain only about 3 to 4 per cent of the ore.

Because of this, the ore must be concentrated before the processing begins. A flotation cell is used for this and other metal ores, particularly lead.

How did the flotation process originate?

One story about the discovery of the process involves the wife of a lead worker in a mining village in Derbyshire, England. While washing her husband's clothes many years ago, she noticed that the suds became darkened rather than remaining white and frothy. Experts found that the darkening was due to tiny particles of galena (lead sulphide). This is reputed to have led to the use of flotation cells to extract the sulphide from the rock.

• *Experiment 1.4 The flotation cell*

In this experiment you are going to concentrate a mixture of sand and copper sulphide or lead sulphide.

Fill the tank to about 5 cm from the top with tap water and add about 700 g of the fine mixture, followed by 0.5 cm^3 of cresol (the frother) and 0.5 g of sodium or potassium ethyl xanthate (the collector). Test with litmus paper to make sure the solution is alkaline. Switch on the agitator and air blower and leave for 5 minutes. Collect in a beaker the froth which overflows. Dilute it with water, and filter it.

Examine the residue. What is it? You could test it to find its constituents. What did the frothing agent do? How did the separation occur? Why was a collector used?

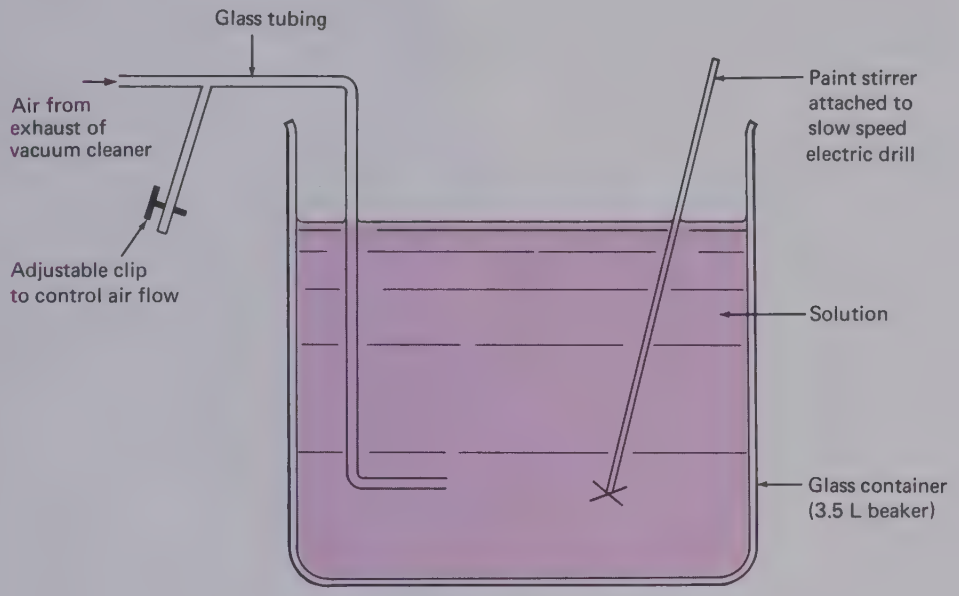

Glass tubing
Air from exhaust of vacuum cleaner
Adjustable clip to control air flow
Paint stirrer attached to slow speed electric drill
Solution
Glass container (3.5 L beaker)

Figure 1-11 The flotation cell

In industrial operations the concentrated sulphide is then roasted to burn off part of the sulphur and then heated in a furnace. The reactions are complex but can be shown by the following equations:

$$2Cu_2S + 3O_2 \longrightarrow 2Cu_2O + 2SO_2$$
$$2Cu_2O + Cu_2S \longrightarrow 6Cu + SO_2$$

What is the function in this process of the sulphur in the ore?

The copper produced must be further purified. It is tapped from the furnace and poured into a converter into which a stream of air is blown. This oxidizes the impurities, which form a slag. Toward the end of the process, methane or propane is injected into the furnace to reduce any remaining copper oxide to the metal.

Figure 1-12 Flotation cells in an Inco Metals Company mill

This copper is about 99.5 per cent pure and when solidified is known as blister copper because of its appearance. For electrical use, the copper needs to be refined further to 99.95 per cent purity by electrolysis in a method similar to the following experiment.

• *Experiment 1.5*
Electrolytic refining of copper

Clean two strips of copper with emery paper. Place them in a beaker containing copper sulphate solution, making sure they are not touching each other. Connect a 12 volt d.c. supply across them. Allow the current to flow for 10 minutes. Remove the electrodes carefully, noting which was which, and inspect them. Why is only the copper deposited? What happens to the impurities in the commercial process?

In industry, the anodes are made from the molten metal from the blister copper and will contain traces of gold and silver, which are recovered as by-products of the refining process.

Nickel

In 1976 Canada led the world in nickel production. Near Sudbury, Ontario, the deposits are the richest ever found. The International Nickel Company (INCO) and Falconbridge Mines both have plants in the area for the entire process of extraction and refining. Other companies, such as Sherritt-Gordon Mines Ltd. in Alberta and Noranda Mines in Quebec, process the concentrated ore from smaller deposits.

The ore in Sudbury is mainly pentlandite, a combined sulphide of nickel and iron. The production method is similar to that for copper and the final purity is achieved by electrolysis. During the roasting, large amounts of sulphur dioxide are produced. This has caused many pollution problems.

All nickel and iron ore requirements for expected domestic needs and exports can be met into the next century from operating mines and from known but undeveloped mineral deposits considered likely to be brought into production.

Metal Mining in Canada, 1976-2000

Again, there are many by-products, notably silver, gold, platinum, iridium and palladium. These are deposited during the final electrolysis.

As much as 75 per cent of the nickel produced is used in alloys with a range of different metals. It increases strength and corrosion resistance. Its best-known use in this way is in stainless steel. Nickel is also used in alloys in the electronics industry. The electroplating of a metal to prevent it from corroding depends on a layer of nickel under the usual chromium finish.

Zinc and lead

Zinc, which is mainly found as zinc blende (ZnS), and lead, found as galena (PbS), are usually mined and processed together. Sites where both minerals are mined and smelted are Timmins, Ontario, and Trail and Kimberley in British Columbia.

The ore is concentrated by flotation, in which the zinc sulphide and the lead sulphide are separated. The zinc sulphide is roasted in multiple-hearth roasters:

$$2ZnS + 3O_2 \longrightarrow 2ZnO + 2SO_2$$

The oxide is then reduced with carbon monoxide or coal:

$$ZnO + CO \longrightarrow Zn + CO_2$$

Where power is cheaper, an electrolytic process can be used.

In nineteenth century England, a merchant died mysteriously. After investigation, it was found that on his way to work each day he stopped at a local inn for some liquid refreshment. As he was always the first customer of the day, the ale he drank had been sitting overnight in the lead piping leading from the barrel to the bar. The verdict: lead poisoning.

The chemistry of lead production is similar but more complicated. The reaction occurs in a blast furnace.

$$4PbS + 7O_2 \longrightarrow 2PbO + 2PbSO_4 + 2SO_2$$
$$PbS + 2PbO \longrightarrow 3Pb + SO_2$$
$$PbS + PbSO_4 \longrightarrow 2Pb + 2SO_2$$

The two processes described below depend on the relative boiling and melting points of zinc and lead. Find out what these are and how they help the processes.

The lead produced often contains silver and can be extracted by the Parkes process. Silver dissolves more readily in zinc than in lead. When both are near their freezing point, they do not mix.

Zinc is mixed with the impure molten lead and allowed to stand. On cooling, two layers are formed: the upper layer contains the zinc, some lead and all of the silver; the lower one contains the lead and a little zinc. The zinc layer solidifies first on cooling and can be removed by distillation.

Since lead and zinc occur together, there is an advantage in being able to produce both in the same process. This was first done in 1957 in England. The roasted ore and hot coke are put in a blast furnace and hot air blown through:

$$ZnO + C \longrightarrow Zn + CO$$
$$PbO + C \longrightarrow Pb + CO$$

The zinc is vaporized but the lead remains molten at the furnace temperature. The lead, therefore, settles and can be tapped. The zinc vapour is condensed.

Galvanizing, to protect a metal from corrosion, accounts for much of the zinc produced. Zinc is also alloyed with copper to make brass. By far the main uses of the lead produced are in the manufacture of the plates in car batteries and as a shield for radioactive material.

Aluminum

Aluminum is such an important metal that its ore is imported from the Caribbean and South America, and processed in Quebec and at Kitimat, British Columbia.

Aluminum oxide cannot be smelted in a blast furnace. Why? This may explain why aluminum was not isolated until 1827 and did not become profitable until the Hall process was devised in 1886.

Although aluminum is the third commonest element in the earth's crust after oxygen and silicon, it occurs mainly in clays. There is no known method for obtaining the metal economically from these materials.

The chief source is the mineral bauxite, which can be represented by the formula $Al_2O_3.2H_2O$, but contains impurities such as iron and silicon. These are removed from the ore as soon as it is mined. The purification process depends on the fact that aluminum oxide and silica dissolve in alkalis, whereas iron oxide does not. The solution containing aluminum and silicon is then treated with

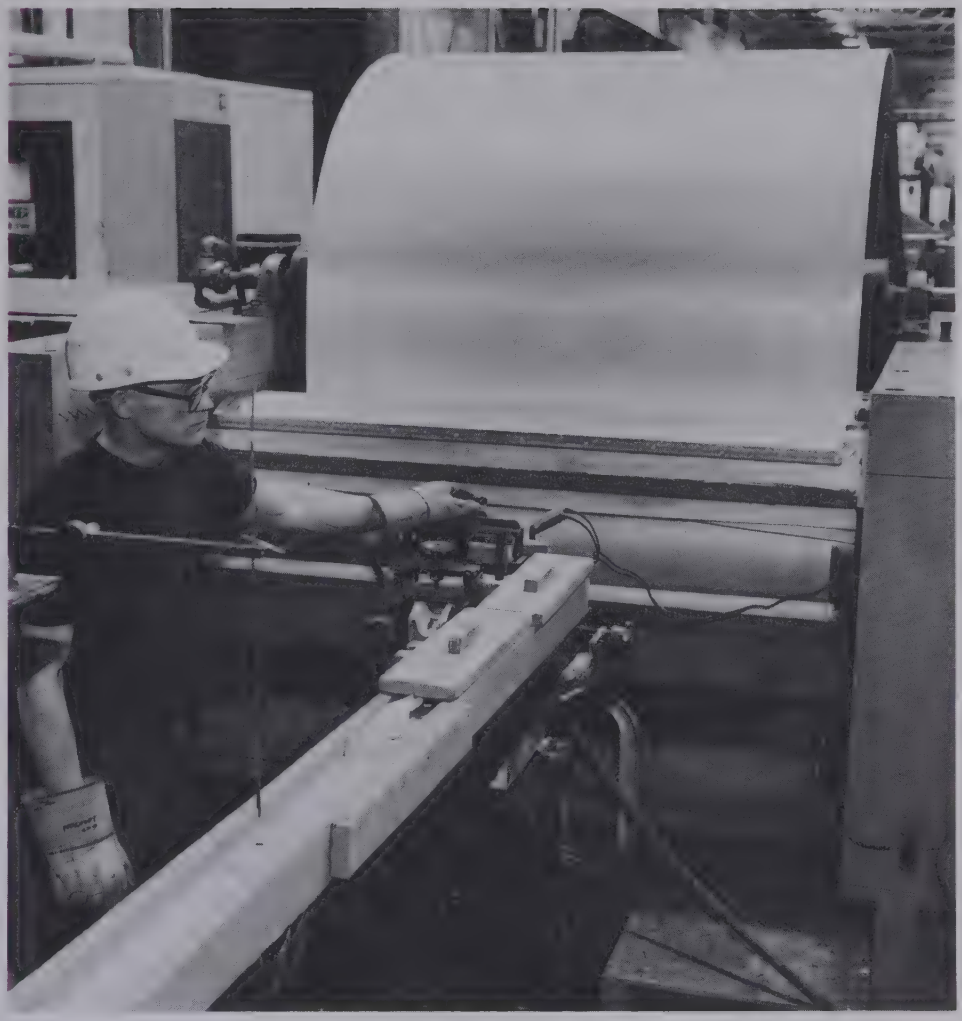


Figure 1-13 Casting aluminum into a continuous sheet from a trough of the molten metal. The sheet, cast at a rate of 101 cm/min, is 146 cm wide and 0.7 cm thick. It is then rolled to a thickness of less than 0.015 cm to produce household foil.

carbon dioxide. Sodium silicate is not affected by carbon dioxide, but sodium aluminate reacts to give sodium carbonate and a precipitate of aluminum hydroxide. This is then heated to give pure aluminum oxide. Can you write equations for these reactions?

All these reactions are carried out near the bauxite mines. The metal is not extracted at this stage. Because of the need for cheap hydro-electric power, which is seldom available in areas where bauxite is found, the purified bauxite must then be transported to the smelting plant. This processing is done in Quebec and at Kitimat, British Columbia.

Because it is light yet strong and highly resistant to corrosion, aluminum has found many uses in the construction of airplanes and, to some extent, in large commercial vehicles, such as buses. Its use in the food industry as a wrapping is clearly evident from a visit to the supermarket.

The aluminum statue of Eros has stood in Piccadilly Circus, London, since 1893. It is a prime example of the metal's resistance to corrosion.

2 Alloying

Why is 'tins' in quotation marks?

Why is a bridge made from steel rather than iron? Why was the propeller for the liner *Queen Elizabeth 2* made from a nickel-aluminum bronze containing about 12 per cent manganese, and not from cast iron or steel as it might have been years ago?

Finished metallic products such as airplanes, ships, cars and even 'tins' for containing foods are seldom, if ever, made from a pure metal. The properties of a pure metal are unsatisfactory for such designs, usually being too soft, too weak and too liable to corrosion. These, and other properties, are improved by alloying.

An *alloy* is a solution of two or more metals or non-metals in each other.

Most commercial alloys, in fact, contain more than two component elements. Try to discover when a pure metal is used other than in a chemical process.

• *Experiment 2.1 Comparing a pure metal and an alloy*

Take six groups of metal strips. Each metal in a group should have the same dimensions.

The groups are

(a) iron, steel, Mumetal
(b) copper, bronze, brass
(c) steel, stainless steel
(d) silver, EPNS (electroplate nickel silver)
(e) lead, tin, solder
(f) iron, galvanized iron

Perform the following tests for one group at a time and compare the results for each metal in that group.

(i) **Hardness**. Scratch the surface of each with a file.
(ii) **Impact (brittleness)**. Hold the sample in a vise with 5 cm protruding from the jaws. Drop a 100 g mass from a height of 1.5 m and observe.
(iii) **Fatigue**. If the sample broke in part (ii), use one of the pieces. Hold the sample with pliers at each end, leaving 3 cm of it between the jaws. Bend the sample backward and forward counting how many bends it takes to cause a fracture.
(iv) **Magnetism**. Test each sample with a magnet to see if is magnetic.
(v) **Strength**. If your school has a tensile tester, a sample of each could be tested for relative strength as a comparison only.
(vi) **Corrosion**. Place each sample in a beaker of dilute hydrochloric acid for 30 minutes and observe.
(vii) Find, from tables, the melting points of each sample.

Why do the properties change?

For simplicity, let us consider a binary alloy (that is, an alloy of one metal and one other substance).

If two molten metals, A and B, are mixed and then solidified, one of three things can happen:

(a) A large amount of A plus a small amount of B may cause B to dissolve in A. The mixture produced is said to be miscible and the grains produced are homogeneous and of only one type. Examples would be copper-nickel and silver-gold.

(b) With roughly equal amounts of A and B (a fairly common type of alloy), not all of B will dissolve in A. The structure of the cooled metal depends on the percentage of A and B. Examples would be copper-silver and lead-tin.

(c) A *totally* immiscible mixture is rare. Examples would be lead-antimony, tin-zinc and bismuth-cadmium. When solidified, the mixture would comprise coherent crystals of pure A and pure B.

When two metals are soluble in each other in solid form, they are said to form *solid* solutions. There are two types, (i) substitutional and (ii) interstitial, (see Figure 2-1).

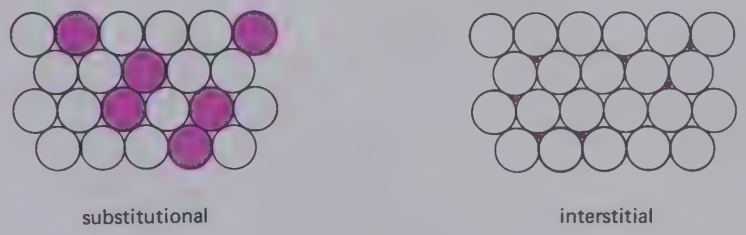


Figure 2-1
(a) Substitutional solid solution
(b) Interstitial solid solution

You may like to investigate the work on solid solutions by W. Hume-Rothery. He proposed that a substitutional solid solution may be formed between two metals if their atoms have a similar atomic radius, if they have the same crystal structure and similar electrochemical potentials. If all these factors occur, he found that a metal of higher valency is more likely to dissolve in one of lower valency.

From the following experiments you will see how the behaviour of one metal dissolving in another affects the properties of each. The different systems (a), (b) and (c) above are studied by means of equilibrium (or phase) diagrams. A *phase* is a homogeneous region with a definite boundary.

Table 2-1 SOME COMMON NON-FERROUS ALLOYS

Alloy	Main Metals	Composition (%)	Main Uses
Aluminum-silicon	aluminum, silicon, some copper	Al:95/Cu:5 Al:88/Cu:12	pressure dies castings
"Duralumin"	aluminum, copper	Cu:4/Mn:0.5/ Mg:0.5/Fe:0.5/ Si:0.5/Al:balance	forgings, bars, sheets, tubes, rivets
Brass	copper, zinc	Cu:85/Zn:15 Cu:70/Zn:30 Cu:65/Zn:35 Cu:60/Zn:40	jewelry cartridge cases cold press work castings, propellers, auto fittings
Copper-nickel	copper, nickel	Cu:98/Ni:2 Cu:90/Ni:10 Cu:80/Ni:20 Cu:60/Ni:40 Cu:70/Ni:30 Cu:30/Ni:70	hard wires under corrosive conditions condenser tubes coins thermocouples electrical resistors turbine blades
Magnesium-zirconium	magnesium, zirconium	Zr:0.72/ Zn:1.3-5.5/ rare earths:1.2-3.0/Mg:balance	light weight, high strength alloy castings
Magnesium-aluminum-manganese	magnesium, aluminum, manganese	Al:1-12/Mn:0.1-1/ Mg:balance	pressure die castings
"Nimonic" alloys	nickel, chromium	Ni-Cr:10-21 with Al, Fe, Co, Mo, Ti	corrosion resistant parts, electrodes, thermocouples
Tin bronze	copper, tin	Cu:95/Sn:5 Cu:90/Sn:10	coins, gun metal, castings for high pressure steam
Bearing alloys	lead, antimony	Pb:90/Sb:10 Pb:80/Sb:20	bearings
	tin, antimony, copper	Sn:87/Sb:10/Cu:3 Sn:89/Sb:7/Cu:4	bearings

● *Experiment 2.2*
Cooling curves for pure and impure substances

Fill a test tube about one-third full with naphthalene and heat it until it melts as shown in Figure 2-2. Insert a 0-100°C thermometer into the naphthalene and record its temperature at 30 second intervals as it cools. Use the thermometer as a stirrer until partial solidification occurs. Continue to record the temperature until the naphthalene has been solidified for 5 minutes. Plot a graph of temperature on the y-axis against time on the x-axis. Can you explain the shape of the graph?

Repeat the experiment using paradichlorobenzene instead of naphthalene and then again with a mixture of equal quantities of naphthalene and paradichlorobenzene.

Your graphs should tell you something about the melting points of a pure and impure substance.

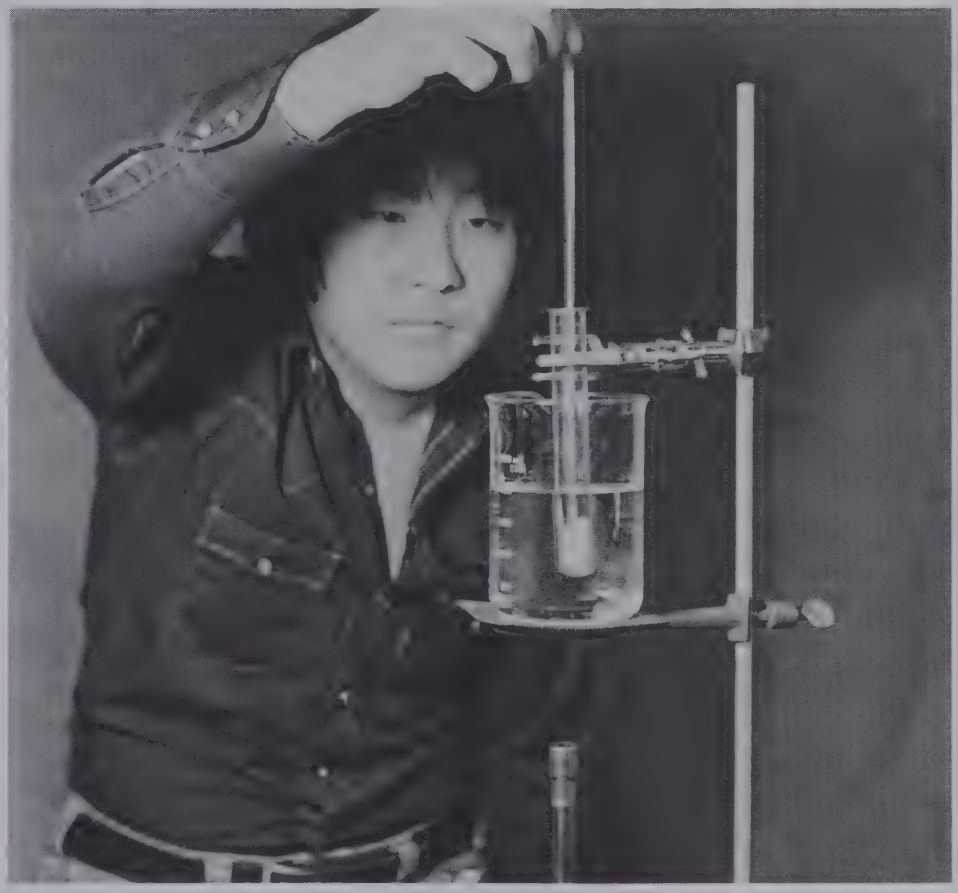


Figure 2-2 Apparatus to find the cooling curve as naphthalene cools

● *Experiment 2.3*
Plotting a phase diagram for two miscible solids

Because it is easier to work with non-metals in the laboratory, two such substances that behave similarly to metals have been selected.

Accurately weigh the mixtures in Table 2-2 and place them in test tubes:

Table 2-2 MIXTURES FOR EXPERIMENT 2.3		
Mixture	Naphthalene (g)	2-Naphthol (g)
A	4.0	1.0
B	3.5	1.5
C	2.5	2.5
D	1.5	3.5
E	1.0	4.0

Different groups could each investigate one mixture.

Hold the test tube 5 cm above a low Bunsen flame. Insert a 0-150°C thermometer in the mixture and continue heating up to 140°C and then turn off the Bunsen. Stir continuously for as long as possible and record the temperature every 30 seconds as it cools.

Plot a graph of temperature against time. The graph should show three distinct parts, two of which are almost straight lines, and the other where the freezing is taking place. Try to determine the ends of the straight lines; these will represent the temperatures used to plot the freezing point (when the first solid appears) and the melting point (when solidification is complete).

Plot the freezing and melting points from each mixture (on the *y*-axis) against percentage composition. Add the melting points of pure naphthalene (80°C) and pure 2-naphthol (122°C). Join the freezing points together by a line (called the *liquidus*) and the melting points by a second line (the *solidus*).

The graph should have three distinct regions. What does each represent?

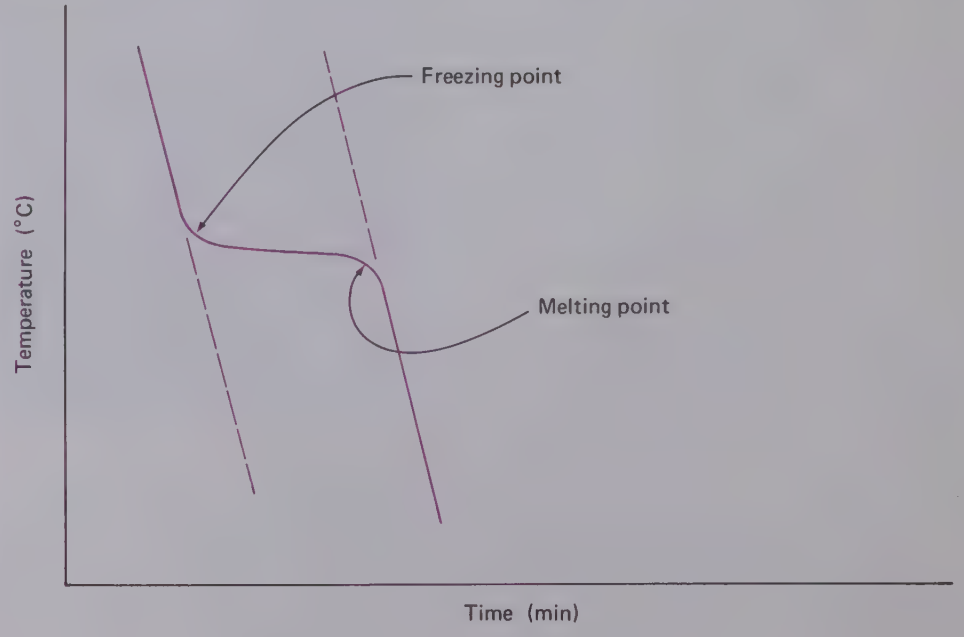


Figure 2-3 A typical temperature-time graph

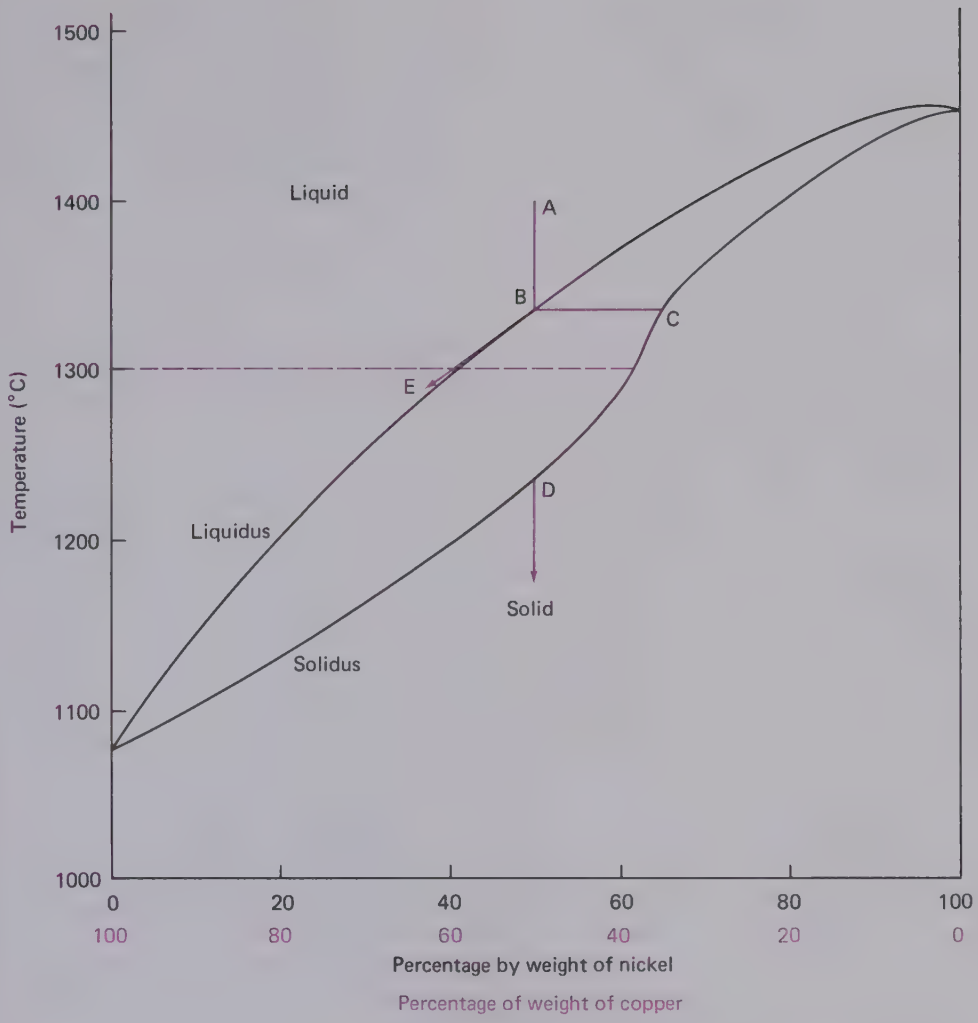


Figure 2-4 Phase diagram for the copper-nickel system

Figure 2-4 shows the phase diagram for the copper-nickel system. Consider an alloy of 50 per cent copper cooling from 1400°C (point *A*). When it reaches a temperature of 1335°C freezing starts, but the composition of the solid is not 50 per cent copper, 50 per cent nickel. Instead, its composition is that shown at point *C* – 35 per cent copper, 65 per cent nickel. When the temperature has fallen to, say, 1300°C, the solid then has a composition of 38 per cent copper. So during the cooling, the solid changes its composition along line *CD* and the remaining liquid also changes along line *BE*. Since the first crystals are richer in nickel, the remaining liquid will be richer in copper than the original composition. So, as cooling progresses, the original crystals absorb copper from the liquid to change their composition. Finally at 1235°C, the solidus line is reached, the liquid vanishes and the solid has the same uniform composition as the completely molten alloy.

What has been described is the ideal case and this does not normally occur in practice. If the cooling is at the normal rate, the solidus line will appear lower. This means the solidification from *C* to *D* will show a steeper line. For a solid to continuously change its composition, diffusion of atoms must occur. This is extremely slow in solids and therefore does not have time to happen at fast cooling rates. Each layer of solid produced will therefore have a slightly different composition from the previous layer.

• *Experiment 2.4 Plotting a phase diagram for two immiscible solids*

The method used is very similar to the procedure in Experiment 2.3.

Prepare mixtures of naphthalene and 1-Naphthol as shown in Table 2-3.

Table 2-3 MIXTURES FOR EXPERIMENT 2.4

Mixture	Naphthalene (g)	1-Naphthol (g)
A	4.0	1.0
B	3.5	1.5
C	3.0	2.0
D	2.5	2.5
E	2.0	3.0
F	1.5	3.5
G	1.0	4.0

Take temperature readings between 100°C and 30°C and plot the temperature-time graphs for each sample. Your observation during cooling, and the graphs, should give you the temperatures of the solidus and liquidus lines at each composition. Construct a phase diagram as in Experiment 2.3 and try to label the different phases. The phase diagram should have a shape similar to that in Figure 2-5.

From your temperature-time graphs, you will see that one mixture behaves like a pure substance in solidifying at a single temperature. This mixture is known as a *eutectic* mixture.

Figure 2-5 shows the phase diagram for the lead-antimony system, which is similar to the one you have just plotted.

Consider an alloy of composition 60 per cent antimony, 40 per cent lead. On cooling from 600°C, the first crystal, of antimony, appears at about 520°C. This leaves the liquid richer in lead. On further cooling, more antimony solidifies and the liquid becomes still richer in lead. The composition of the liquid at any temperature is found by reading the composition on line *FE* at that temperature. When everything is solidified, the alloy will consist of antimony embedded in a mixture of the eutectic, and lead dissolved in antimony (13 per cent antimony, 87 per cent lead).

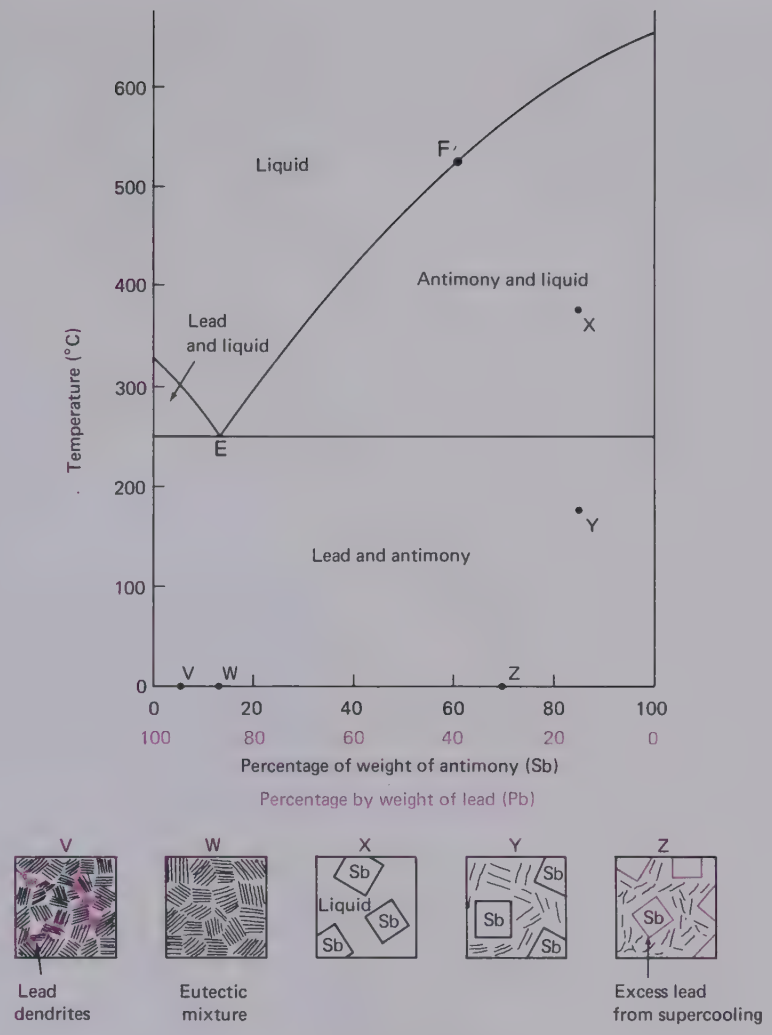


Figure 2-5 Phase diagram for the lead-antimony system and microstructures at various points

Use the phase diagram to predict what would happen if an alloy of 95 per cent lead were allowed to cool.

What would happen if the eutectic mixture (87 per cent lead) were cooled? Does it differ from a pure metal? How would the solid appear under a high-power microscope? Try to find out about the importance of a eutectic mixture.

• *Experiment 2.5*
Plotting the most common phase diagram for metals

This represents the system for metals where there is a definite limit for the amount of metal *A* dissolving in *B*. You will investigate the lead-tin system. Each group should prepare one of the alloys from Table 2-4.

Table 2-4 ALLOYS FOR EXPERIMENT 2.5

Mixture	Tin (%)	Mass tin (g)	Mass lead (g)
A	5	3.0	57.0
B	10	6.0	54.0
C	15	9.0	51.0
D	20	12.0	48.0
E	30	18.0	42.0
F	50	30.0	30.0
G	60	36.0	24.0
H	70	42.0	18.0
I	80	48.0	12.0

Melt the lead in the crucible and add the tin in small quantities. Stir gently with a nickel spatula and also use it to remove any scum formed. Sprinkle the surface of the melt with powdered charcoal. Gently lower the copper tube into the metal and put the asbestos lid in place. You may have to hold the copper tube down with a pair of tongs. Place the thermometer in the copper tube and heat to 360°C. Remove the Bunsen and allow the metal to cool. Take temperature readings every 15 seconds. Plot a cooling curve, and then collect those from the other groups.

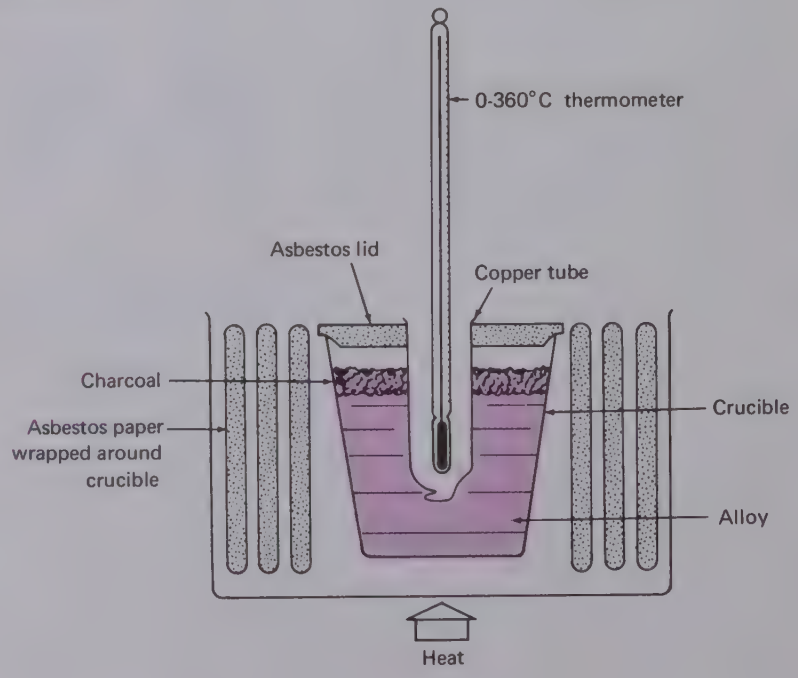


Figure 2-6 Apparatus for the cooling of a lead-tin alloy

These graphs will show you the temperatures for the liquidus line by means of the break in the curve. Plot these temperatures on a phase diagram of temperature against percentage composition.

A second break in the smooth curves in most of the graphs will give you the solidus temperatures. If you are in doubt, refer back to Experiment 2.3 for the method.

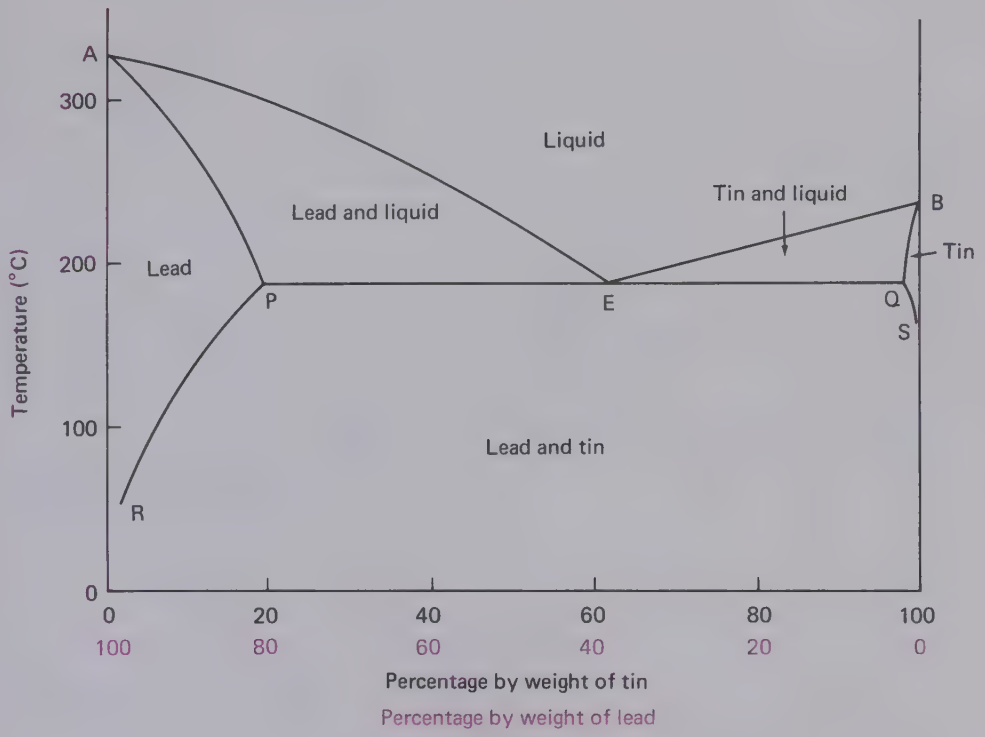


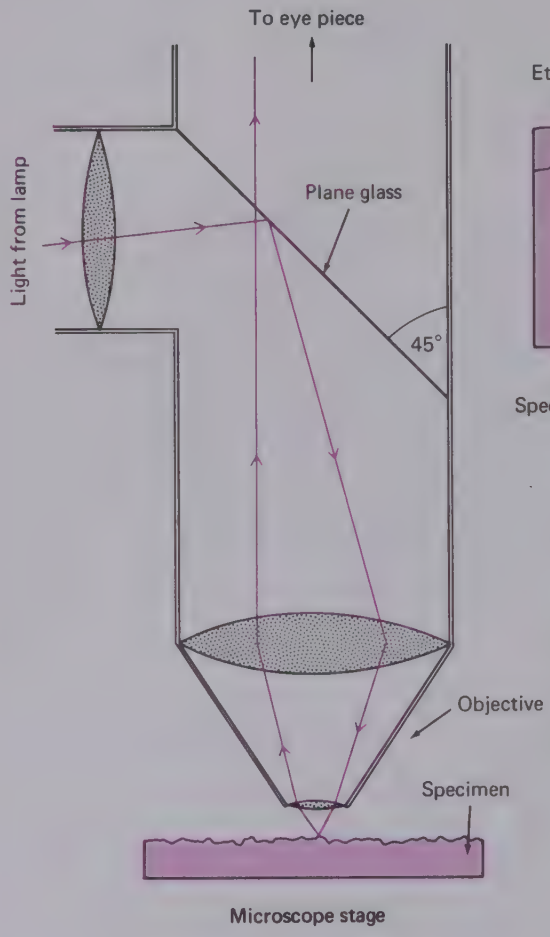
Figure 2-7 Phase diagram for the lead-tin system

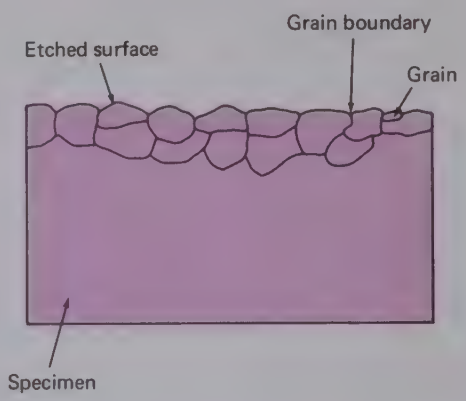
The phase diagram you get should look like that in Figure 2-7, although you will find that the lines *PR* and *QS* will be missing.

From what you have learned already, can you predict what would happen if molten metals of composition 35 per cent tin, 62 per cent tin and 85 per cent tin were cooled? How would the final solids differ?

Microstructures

A microstructure is a magnified view of a metal. If the metal is etched, the etchant will eat away the grain boundaries and those between each phase. This shows the distinct regions present.





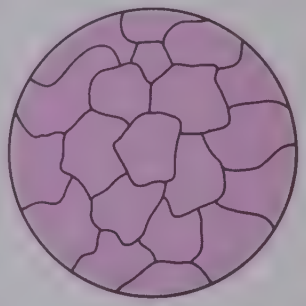


Figure 2-8 (a) The metallurgical microscope

Figure 2-8 (b) Cut-away side view of an etched specimen

Figure 2-8 (c) Microstructure as seen through the microscope

• *Experiment 2.6*
The microstructure of lead-tin alloys

You may wish to use some of the alloys made in Experiment 2.5, but it is likely your teacher will want to re-use these alloys.

For this experiment you will investigate the microstructure of three alloys: 30 per cent tin, 62 per cent tin and 85 per cent tin.

Table 2-5 ALLOYS FOR EXPERIMENT 2.6

Mixture	Tin (%)	Mass tin (g)	Mass lead (g)
A	30	3.0	7.0
B	62	6.2	3.8
C	85	8.5	1.5

Weigh out the tin and lead accurately and melt each mixture in an ignition tube with a low Bunsen flame. Stir and allow to cool. Using goggles, carefully break the tube with pliers and cut the sample across its length with a hack-saw. File the surface and grind it to as smooth a surface as possible using successively finer emery papers. Use papers of grit 1, 0, 00, 000 and 0000 (silicon carbide paper). Attach them to a flat surface and move the sample over them. Grind in one direction only for each paper and then change the direction of grinding by 90° for each successive paper. You will find this easier if you dampen the emery papers with water or, better still, kerosene. Do not press hard. Finish the polishing with a metal polish and a soft rag. Wash the sample under the tap.

Carry out the following procedure under a fume hood and avoid breathing any vapours. Wear rubber gloves. Immerse the sample for 1 minute in a mixture of 10 cm^3 concentrated nitric acid, 10 cm^3 glacial acetic acid and 40 cm^3 glycerol. Use extreme caution with this etchant, handling the sample at all times with tongs. Remove the sample, wash it thoroughly and allow it to dry.

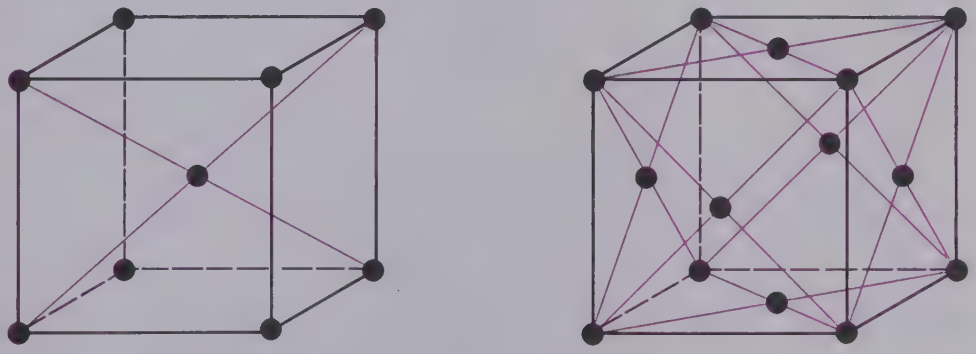
View the etched surface under a microscope and sketch the microstructure. A metallurgical microscope is best for this since the sample is illuminated from above by a lamp contained in the microscope, as shown in Figure 2-8. A standard microscope can be used, particularly at low magnifications. The sample is illuminated obliquely by light sources at either side. This causes the lighter parts of the microstructure to appear dark and vice versa, as they would be under the metallurgical microscope.

How do the microstructures compare with your predictions after Experiment 2.5? Can you explain what you see by referring to the phase diagram for the lead-tin system?

Steel: the iron-carbon system

Atoms can be packed together in different ways. You should try to discover some, using ping-pong balls.

Figure 2-9 shows two ways known as body-centred cubic (b.c.c.) and face-centred cubic (f.c.c.).



(a) Body-centred cubic

(b) Face-centred cubic

Figure 2-9 Atomic packing
(a) Body-centred cubic
(b) Face-centred cubic

Pure iron exists in both forms but at different temperatures, i.e., iron is *allotropic*.

The system for iron is

$$\text{b.c.c. } (\alpha) \underset{910^\circ C}{\overset{937^\circ C}{\rightleftharpoons}} \text{f.c.c. } (\gamma) \underset{1399^\circ C}{\overset{1400^\circ C}{\rightleftharpoons}} \text{b.c.c. } (\delta)$$

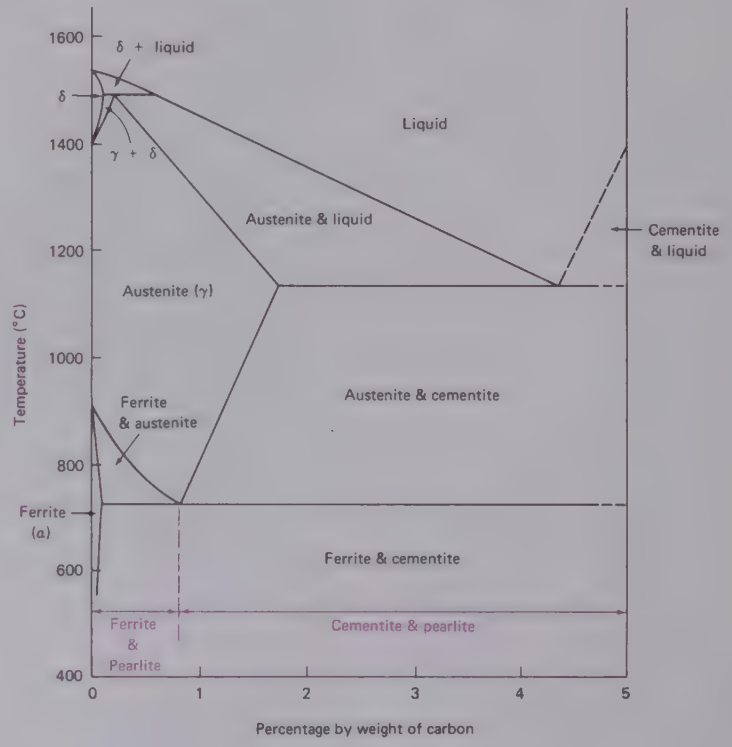


Figure 2-10 Phase diagram for the iron-carbon system

The b.c.c. types can dissolve only very small amounts of carbon, forming either *ferrite* (α) or δ-*iron* depending on the temperature (see Fig. 2-10). However the f.c.c. type can dissolve up to 1.7 per cent carbon, forming a solid solution, *austenite* (γ).

Cementite, an intermediate phase, is also formed from iron and carbon.

If 0.87 per cent carbon alloy is cooled, the first solid formed will be austenite, which at 723°C further separates into a mixture of ferrite and cementite. This mixture appears similar to mother of pearl when etched and is called *pearlite*.

What is "mild" steel?

Ferrite is soft and ductile while cementite is hard and brittle. This should give you some idea of why steels with different percentages of carbon are needed for various uses.

What is "high-carbon" steel?

What will the final polished and etched solid look like if the original molten liquid contains (a) 0.3 per cent carbon, (b) 1.4 per cent carbon? How will the properties of each be affected by their structures?

• *Experiment 2.7*
Microstructure of carbon steels

Grind three specimens of annealed steel containing (a) 0.1 per cent carbon, (b) 0.4 per cent carbon and (c) 1.2 per cent carbon. Use the technique described in Experiment 2.6. Polish the samples with metal polish; wash and etch them using the precautions outlined in Experiment 2.6. The etchant to be used is 2 per cent nitol (2 per cent solution of concentrated nitric acid in ethanol) and the samples should be immersed for 30 seconds. Etching is completed when the original shiny surface becomes frosty. Examine the surfaces under the microscope.

In the first two samples you would expect to see ferrite (which appears light) and pearlite (dark). It is not possible to see the two constituents of pearlite (ferrite and cementite) at this magnification. The high carbon sample still shows pearlite, which may show its ferrite and cementite, and the lighter cementite surrounding it.

Figure 2-11 microstructure of 1.2 per cent carbon steel (× 200)
The light coloured lines are cementite surrounding the grains of austenite. The grains show the pearlite, which consists of two components, ferrite and cementite.

Check with the iron-carbon phase diagram to see why the microstructures appear as they do.

Other forms of steel can be made by quenching and tempering. The addition of such elements as silicon and magnesium also causes alteration of the properties. Your teacher will be able to describe these if you are interested.

Summary

You have seen that the presence of a second material causes a variation in the freezing point and causes the mixture to solidify over a range of temperatures.

The final solid produced depends upon the relative amounts of each material. This also accounts for the final structure of the solid and it can be predicted by reference to the phase diagrams.

The most important prediction, however, is that of the properties of the final solid. If we know the properties of each phase, we can then arrange the composition to give us what we require.

3 Treatment and testing

A metal which is cast, rolled or forged may not have the properties required of it. These properties can be altered by treating the metal either during or after production. One way is galvanizing, which is discussed in Chapter 4. However, the most common method, particularly for ferrous metals, is heat treatment.

Treatment

• *Experiment 3.1*
Heat treatment of steel

You will be supplied with three steel hairpins.

(a) Heat the first pin in a Bunsen until it is red hot (about 800°C). *Slowly* remove it from the flame over a period of 2 minutes to cool it gradually. This process is called *annealing*. Label this sample *A*.

(b) Heat the second pin as in (a) and then plunge it directly into a bucket of cold water. This process is called *quenching*. Label this sample *B*.

(c) Repeat part (b) with the third pin. Then dry it and remove any scale with emery paper. Now heat it at about 300°C by holding it in the tip of the outer flame of a Bunsen. This process is called *tempering*. (You can find this temperature by holding a 0-360°C thermometer in the flame.) Allow this sample to cool normally by placing it on an asbestos mat. Label it sample *C*.

Test each sample for hardness by scratching its surface with a file. Try to bend each hairpin in your fingers. Record your results.

Another test that may be done in a metallurgical laboratory is the Izod or Charpy test, which measures the brittleness of a specimen. A weighted pendulum is raised to a standard height and allowed to strike the sample, which has had a notch carved in it. The striking energy is 163 joules and a pointer indicates the amount of this energy absorbed by the sample in fracturing. This is done by measuring the amount of "follow through" of the pendulum.

You will recall from Chapter 2 that if molten steel in the form of austenite is cooled, the resulting structure is one of ferrite and cementite. If the steel is cooled very quickly as in sample *B*, the equilibrium conditions (which a phase diagram always represents) are not achieved. This time a supersaturated solution of carbon in iron is formed as the carbon cannot be precipitated quickly enough. It is held in the iron lattice and the result, *martensite*, is very brittle and hard.

If this martensite is now tempered as in sample *C*, the carbon is precipitated as cementite, which will decrease the hardness and brittleness.

What happens to a metal under stress?

If a stress is applied to a metal, it deforms. On removal of the stress, the metal may return to its original state (*elastic deformation*) or remain deformed (*plastic deformation*). See Figure 3-1.

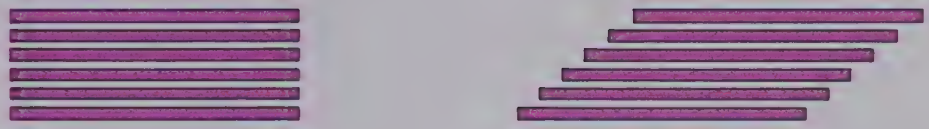


Figure 3-1 The effect of shear on a metal. The atoms are originally arranged in planes. If a shear stress is applied, the deformation produced would be as shown in (b). Each plane, and therefore each atom, has moved the same distance.

Under stress the atoms or planes of atoms may move from their normal position. If the bonds between adjacent planes are broken, the deformation will be permanent.

If the atoms were arranged regularly, the metal would deform easily, but in practice great stress is required. This suggests that there are imperfections in the arrangement. We call these imperfections *dislocations* and they can move through a metal. Think of a dislocation as a half-plane of atoms (an incomplete plane) between two complete planes. See Figure 3-2.

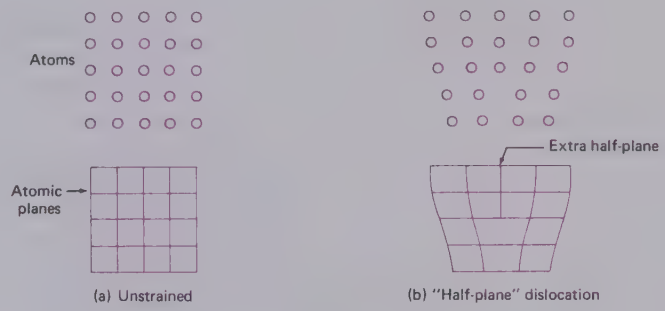


Figure 3-2 A simple dislocation

- *Experiment 3.2 The bubble raft*

Mix a solution of about 1:9 of liquid detergent to water. Place a petri dish on an overhead projector and fill the dish with the mixture to a depth of about 0.5 cm. Burst any bubbles on the surface.

Heat a piece of glass tubing and draw it out into a capillary, breaking it so the open end is about 0.5 mm in diameter. Connect this capillary to the gas supply by means of rubber tubing. (If a gas supply is not handy, an inflated balloon can act as a substitute.)

Place the end of the tube just under the surface in a constant position and turn the gas on gently. When the dish is about three-quarters covered with bubbles, turn off the gas.

Inspect the surface. Are the bubbles arranged regularly?

Gently blow on the surface to represent plastic deformation. Record what you see. Pop a few bubbles at random to simulate a vacancy in the metal lattice. What happens?

Introduce a few larger bubbles to represent solute atoms by using a larger capillary tube. Again, record your results.

Can you find parts of the new pattern which would correspond to grain boundaries in a metal? Can you see dislocations of bubbles? What happens to these dislocations at a grain boundary? Do the dislocations move when stress is applied (by blowing on the surface)?

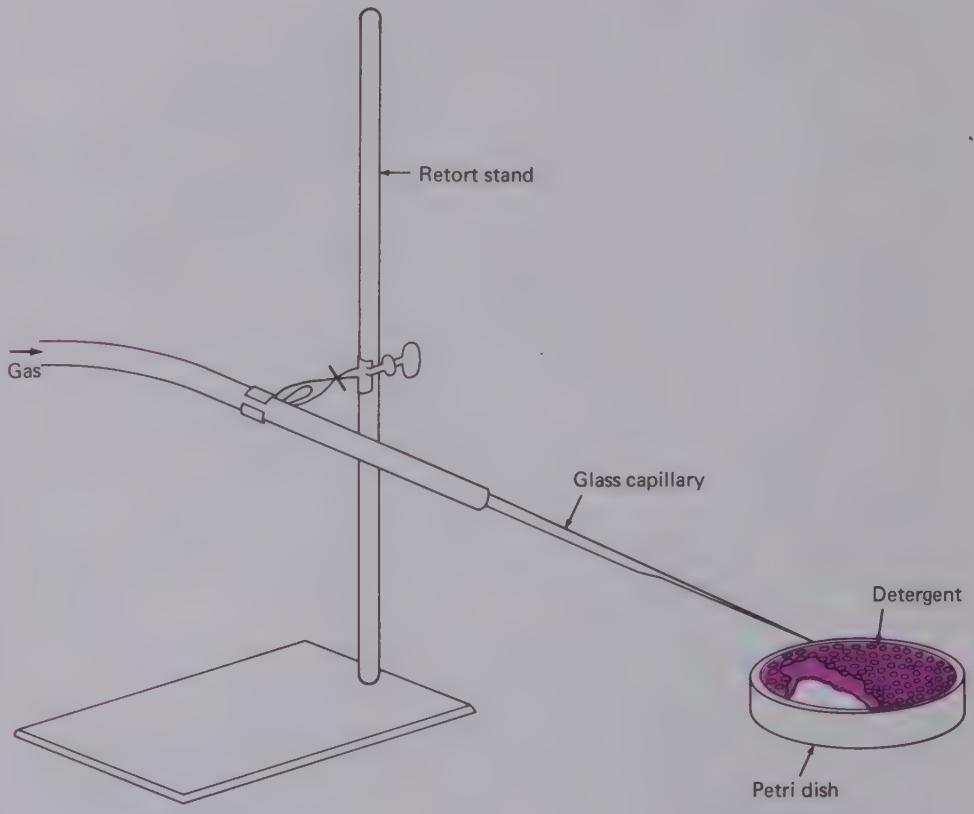


Figure 3-3 Producing a bubble raft

How do dislocations alter the properties of a metal?

As a stress is applied to a metal, the dislocations move. These dislocations are ended at the grain boundaries, so forming a dislocation barrier. It is here that the stress on a metal acts inside that metal.

The more dislocations a metal has, the more difficult it becomes for a dislocation to move. Consequently, the metal becomes harder. This is an example of *work hardening*. Railway rails, for instance, are subjected to stress each time a train passes and therefore they become harder with time. You could try taking a piece of lead and bending it backward and forward until it breaks. It is not difficult to see that the broken edges, where the stress was concentrated, are harder than the rest.

Destructive testing

A tensile test investigates the strength of a metal when pulled by forces in opposite directions. It will also indicate whether the deformation is elastic or plastic. (Recall what these terms mean.)

• *Experiment 3.3 Tensile tests*

(a) You will probably be familiar with the Hooke's Law test in which a spring is loaded and unloaded and the extension of the spring measured. If you are not, ask your teacher to show you. The same experiment can be done using copper wire coiled into a spring. The graphs of load against extension both for the loading and unloading process will tell you the difference between the behaviour of steel and copper.

(b) In this experiment you are going to investigate three different metals in the form of wires. The three types you should use are copper, brass and iron, each about SWG 20.

Straighten them by clamping one end in a vise and pulling the free end with pliers. Cut them into 10 cm lengths.

Remove any stresses in the wires by placing them in a porcelain boat, covering them with powdered carbon and heating them in a furnace for about an hour at 450°C. Allow the wires to cool, dip them briefly in dilute nitric acid, then wash them clean with water. Dry them by dipping in alcohol. Do this under a fume hood and wearing rubber gloves.

Polish the copper and brass wires very gently with a metal polish, taking great care not to bend them. Inspect the surface of each under a microscope and record any surface markings.

Mount one of the samples in the tensile testing machine (your teacher will help you with this) and increase the load until the sample breaks. Record the load (in kg) and the extension (in mm). Repeat this for the other samples.

Plot a graph of load against extension, marking all three curves on the same graph. When you compare the three curves, state the similarities and differences. Label the regions of elastic and plastic behaviour. Which is the strongest and which is the most *ductile*.

According to the *Guinness Book of Records*, 28 g of gold, the most ductile metal, can be drawn into a continuous wire thread of 0.005 mm diameter to a length of 69 km.

Inspect the surface of each sample under the microscope. What changes do you see? Can you decide what happened when the metals were stretched? What does the surface tell you? Refer back to the section on dislocations (page 31) if you have trouble.

Non-destructive testing

In the tests so far, the samples have been destroyed. This is obviously not desirable for every casting and several non-destructive tests are used.

• *Experiment 3.4 Magnetic dust method*

Mix 2 g of fine iron oxide with 25 cm^3 of kerosene in a beaker. Caution: kerosene is inflammable. Put a steel bar to be tested into the field of an electromagnet or strong permanent magnets and carefully pour the iron oxide suspension over the sample. If there is a crack (which may not be visible) on the surface, the sides will become opposite poles and the particles will collect at this crack.

• *Experiment 3.5 Fluorescent test*

This method is particularly useful for non-ferrous metals which are non-magnetic. Dip any metal casting or forging in a bath of fluorescein which will penetrate the cracks. Remove it from the bath, wash it under the tap, shake off the excess water and dust it with lycopodium powder. View the sample under an ultraviolet lamp. Do not look at the lamp directly. Any cracks or surface defects will be shown by the fluorescence.

• *Experiment 3.6 Making a sulphur print*

Sulphur is a common impurity in a ferrous forging and the sulphur print will show not only the distribution of the sulphur but also the flow lines in the metal.

Cut the steel forging supplied and grind it smooth, first with a file and then with emery paper. Soak some photographic printing paper (exposure to light does not matter) in 2 per cent sulphuric acid for 2 minutes. Drain the paper and put it face up on a piece of card. Place the smoothed face of the forging in good contact with the paper, pressing it down with your hand. You can check the progress of the print by carefully raising one edge of the forging and inspecting the paper. If the paper has not darkened enough to see a pattern, replace the forging without altering its position on the paper.

When a pattern is clearly visible, remove the paper, rinse it in water, fix in hypo and wash and dry it.

What do the dark areas mean? Why do you see lines in the rest of the print? How were they formed?

4 Corrosion

For an introduction to the study of corrosion, you should work through Experiments 4.1 to 4.15 in *Chemistry of the Car* in this series written by Joe Hammill and Ken Ashcroft.

You will have learned that corrosion is the biggest single factor in the depreciation of a car. Each year the major manufacturers introduce "improved" corrosion resistance. New steel alloys in the bodywork appear and the sheet is coated in protective primers and paint. Parts more liable to damage such as the bumpers are electrolytically plated, first with nickel, which gives the major corrosion protection, and then with chromium, which produces a finish very much harder and therefore less likely to be scratched. Chromium also produces a shiny, more pleasing finish than nickel alone, which would become very dull quite quickly.

Figure 4-1 Part of a corroding car. Corrosion is the largest factor in the depreciation in value of a car.

Other innovations include the use of galvanized steel in increasing quantities but with a subsequent increase in production costs. Experiments in using plastics in joints and sealers have multiplied and more plastic-based materials have been introduced to the underside to reduce dents and scratches, both starting points for corrosion, from flying stones.

The spring of 1977 saw the Canadian and provincial governments introduce a voluntary code requiring 1978 vehicles to last three years without serious body rust and six years without structural damage from rust. Initial reactions to this varied. The Ford Motor Company of Canada has indicated that it can meet these requirements but General Motors of Canada would not make a commitment. General Motors argued that most of the blame for early rusting lay with the owners' failing to provide proper maintenance such as regular washing underneath and attending to surface markings.

Road and railway bridges present similar problems. Exhaust gases from locomotives contain many corrosive compounds, particularly water vapour and sulphur products. Again, galvanized steel is often used for such bridges but it is not uncommon for authorities in charge of such structures to employ main-

tenance workers permanently assigned to that structure. As soon as one end is reached, the other needs attention again and the maintenance becomes a continuous process.

The major cause of rusting on road bridges is the salt used to melt the snow and ice in the winter. One of the main arteries into Toronto is the Gardiner Expressway, 8 kilometres of which is an elevated six-lane ramp. Rust eats through the paint on the steel girders and spreads underneath. Constant sandblasting down to the bare metal and repainting reduces the problem but the method is only good for about three years before more attention is needed. Three coats of paint are used over the metal, the first being red lead paint. An obvious side effect of such maintenance is research into protective paints. One section of the Expressway has been painted with a new one-coat paint which, it is claimed, will protect for six years.

As you can see, galvanized steel has grown in use, but what is galvanized steel? The activity series of metals (Table 4-1) shows that zinc is more active than steel. This means that if an electrolytic cell is set up between zinc and steel with the surrounding atmosphere providing the electrolyte, the zinc will lose electrons more readily and so zinc ions will be released into the solution. The steel is consequently protected from any corrosion.

The steel is electrolytically coated in a thin layer of zinc after its manufacture and working. This coat not only gives the protection as described, but the oxygen in the atmosphere also produces a thin but dense layer of zinc oxide on the surface and this acts as a barrier coating.

Apart from the uses already mentioned, galvanized steel is being used for roofing, eavestroughs and downspouts, furnace ducts, doors and window frames.

In 1972, the Steel Company of Canada built Stelco Tower, a 26 storey office block, in Hamilton, Ontario. It was built with "rusty steel". This steel, called *Stelcoloy*, contains nickel and copper and rusts on exposure to the atmosphere. However the oxides of both the nickel and copper build up at the surfaces forming a protective layer which prevents further rusting. It is estimated that it takes from five to ten years for the process to be completed but the final rusty appearance is not to the liking of everyone!

Figures 4-2 (a) and 4-2 (b) show how Stelcoloy steel, also known as weathering steel, compares with a normal carbon steel in terms of thickness losses due to corrosion. You can see that the surface thickness of the Stelcoloy decreases at a slower rate than that of conventional steel.

This weathering steel has been used in building bridges, ship loaders, highway light standards and sign supports as well as for buildings. It was used as a roofing material for Silverthorne Collegiate Institute in Toronto and for some parts of the walls. Metal sculptors are using it more and more often in their work for a striking effect. One of many bridges built using welded girders of Stelcoloy is that which carries the Canadian National Railway over the Athabasca River about 300 kilometres northwest of Edmonton, Alberta.

Table 4-1 The activity series for metals

Potassium
Sodium
Calcium
Magnesium
Aluminum
Zinc
Steel
Cast iron
Tin
Lead
Nickel
Brass
Copper
Cupro-nickel
Mercury
Silver
Gold

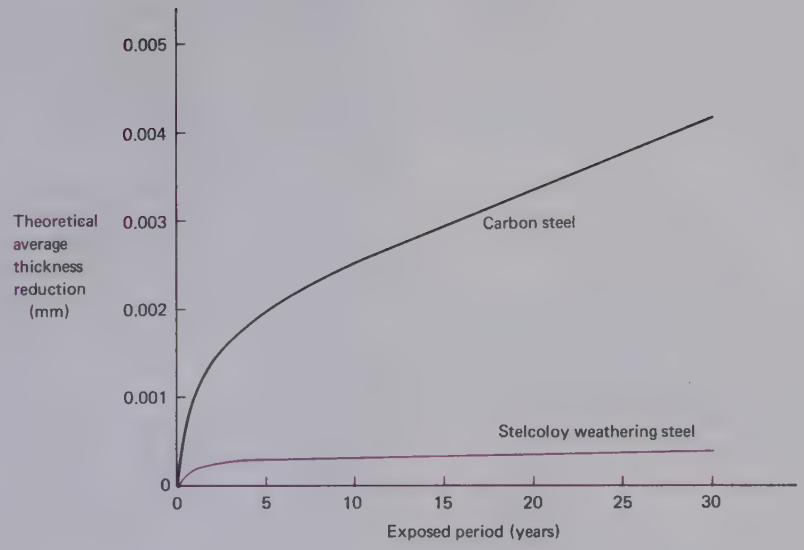


Figure 4-2 (a) Stelcoloy and carbon steel: corrosion in an industrial atmosphere

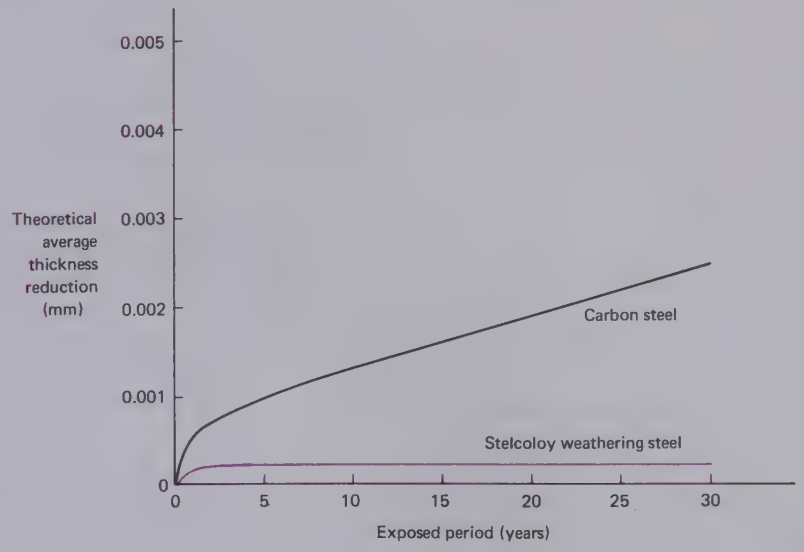


Figure 4-2 (b) Stelcoloy and carbon steel: corrosion in a semi-rural atmosphere

If you keep your eyes on the newspapers, you will find reports appearing regularly about corrosion problems and how it is attempted to rectify them. You should collect such papers for a couple of weeks and see what you can learn about anti-corrosion techniques.

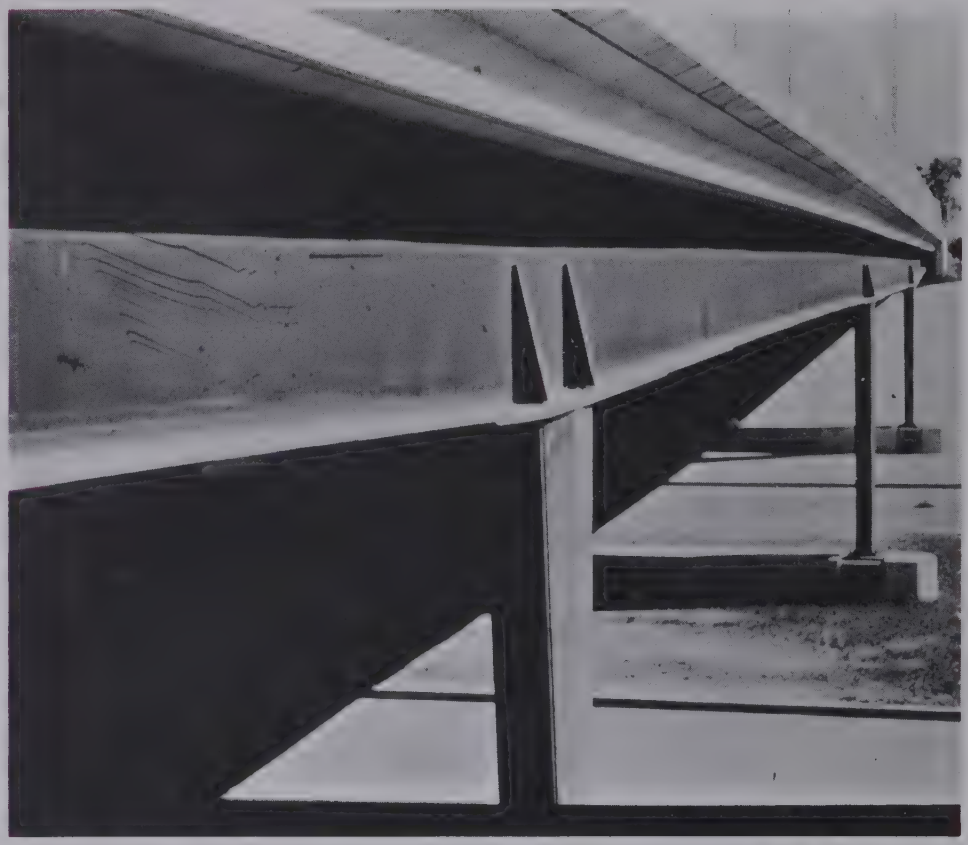


Figure 4-3 156th Street overpass, Edmonton. The girders of this bridge are of Stelcoloy weathering steel. On the left of the photograph you can see imperfections in the surface of the steel. In Chemistry of the Car, page 36, you can learn how a scratch in ordinary steel "pits" or grows deeper. Why will scratches in weathering steel not pit?

5 *"Minor" and "modern" metals*

When the word metal is mentioned, you probably think of iron and steel, copper, aluminum and tin, and maybe nickel, lead and zinc. Further thought may produce a few more examples. Today's metal industry increasingly uses what, in 1950, were considered to be 'exotic' metals.

With new developments in the electronic, nuclear and space fields, more and more different metals are being introduced. It is difficult to keep abreast of all the new uses.

Titanium

Why is a metal cold to the touch on a hot day, while plastic is not?

Aircraft, missiles and rockets need to withstand higher temperatures than before and in tougher conditions of wear and flight. Metals which are lighter, harder and more resistant to wear, stress and fracture are needed.

The use of titanium is an example. You can see how its use has grown by noting that in 1948, three tonnes were produced. By 1974 world production of titanium exceeded 45 000 tonnes; of this amount the United States produced nearly 16 000 tonnes.

Titanium dioxide is used as a whitening additive in paints, but titanium's main use is in the aircraft industry. Its major properties of being light, corrosion-resistant, strong and ductile (which allows it to be shaped easily) make it ideal for aircraft.

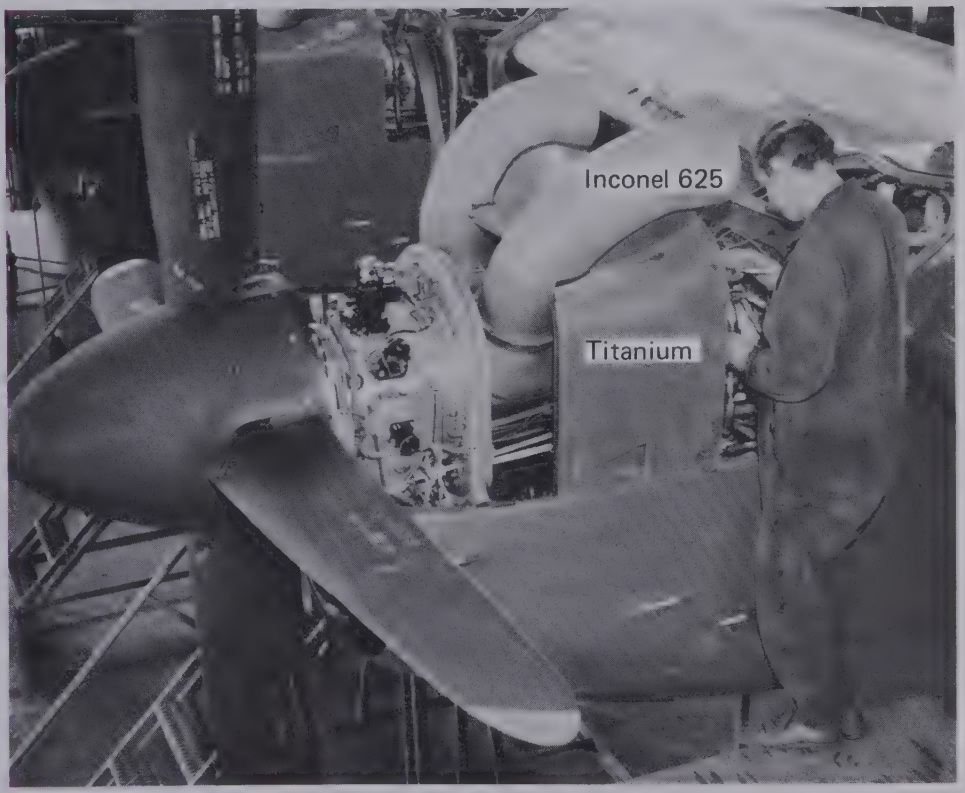


Figure 5-1 Engine of the DeHavilland Dash 7

The DeHavilland Dash 7, a turbo-prop airplane capable of very short, steep take-offs and landings, uses commercially pure titanium in the engine cowlings, primarily because of its good heat resistance. The engine air exhaust nozzle parts use Inconel 625 which is a nickel-based alloy with between 20 and 23 per cent chromium and smaller quantities of molybdenum, iron, niobium, tantalum, cobalt, manganese, silicon, aluminum, titanium, carbon and sulphur. This alloy also has good resistance to heat and also to oxidation. Other parts such as the ducting systems, combustion chambers, thrust reversal assemblies, fuel nozzles and afterburners use the Inconel 625 for the same reasons and also because it has good welding properties.

Beryllium

How does beryllium keep the outside of a space capsule cool by evaporating? What is latent heat?

Beryllium, once considered the most promising metal, has a high melting point (1278°C), good corrosion resistance and strength-to-weight ratio. The problem is that it is very difficult and costly to produce, and very toxic.

U.S. manned spacecraft have used beryllium in the heat shield. Since it has high heat conductivity and specific heat capacity it helps shield the craft from the tremendous heat produced by friction during re-entry. The beryllium absorbs this heat and the metal (a) conducts the heat away and (b) evaporates, thus cooling the surrounding parts.

Figure 5-2 The Apollo 10 space capsule after its 1969 journey. The wear on the outside was mainly caused by friction with the earth's atmosphere. Gene Cernan (left) and John Young are the two astronauts.

Palladium and platinum

Platinum is used in anti-pollution devices in cars (where it helps eliminate the hydrocarbons and carbon monoxide from the exhaust), and also in glass-making. However, it is now often being replaced in other industries. Economy is the main factor and new methods of extraction and processing of metals account for its displacement. Nowadays, electrical contacts in telephone speech circuits and catalysts in chemical reactions generally use palladium rather than platinum. Platinum has also largely been replaced by iridium in the tips of spark plugs in areo engines.

Uranium

Uranium is refined from uranium oxide, which is mined at Elliot Lake, Ontario, and in the United States, Australia, South Africa and France. When uranium, the largest natural atom, is bombarded with neutrons the nucleus splits, producing large fragments. However, the total mass of the uranium and the bombarding neutron has been found to be greater than the total mass of the fragments produced. Some mass is lost and has become converted to energy. (Read pp. 24-25 and 188-189 of *Action Chemistry*) More neutrons are also liberated which then behave as missiles to attack other uranium atoms. This produces a chain reaction

Figure 5-3 The interior of a Canadian nuclear research reactor. The fuel rods and control rods dip down into a large tank of water, which slows down the neutrons. The radiation is caused by particles giving up their energy as they leave the fuel rods and enter the water. This makes the reactor give out a blue glow. The rods you can see are about 2.8 metres long.

which releases great amounts of energy. One estimate claims that in a sustained chain reaction, 1 kg of uranium can release as much energy as 3 000 000 kg of coal. This atom-splitting process is known as *nuclear fission*. Uranium is used as the fuel in many nuclear power stations.

Whiskers

You may recall from Chapter 4 that when a metal is stressed, the stress load builds up at a dislocation barrier. The strength of a metal can be improved if this stress is transferred to a 'more solid' part. To this end, much work has been done on single crystals.

A single crystal, known as a *whisker* or *fibre*, can be grown by electrolysis or vapour condensation, among other ways, and is a few millionths of a metre thick and a few millimetres long. It has a great strength and groups of these fibres embedded in a metal carry the stress load.

The tensile strength of pure titanium can be improved by up to 75 per cent at 500°C by adding molybdenum fibre of 0.0125 cm diameter. Tungsten fibres are also added to nichrome (a nickel-cobalt alloy) and stainless steel. Rocket nozzles have used a copper-tungsten whisker in the copper component.

Semi-conductors

The growth of the use of transistors and the printed circuit has led to the use of semi-conductors such as germanium and the "semi-metals" silicon and boron. The theory of semi-conductors is beyond the scope of this book but you may like to investigate it yourself.

Other metals

What is Molyslip and what does it do? Molybdenum disulphide is a direct derivative of the metal and is commonly used in the lubricants of an automobile.

Metals used in nuclear reactors present a problem in that they need rather different properties from usual. Niobium and zirconium do not absorb neutrons readily, which makes them useful for the support brackets and fuel cans in a reactor. Boron and hafnium absorb neutrons and they are therefore used in the control rods, while molten lithium is sometimes used as the heat transfer agent because of the large range between its melting point (186°C) and its boiling point (1336°C).

Cesium is used in atomic clocks in which time intervals and frequencies are measured to one part in ten thousand million. Silver, apart from its use in jewelry and as an electrical conductor, plays an important part in photography (see *Chemistry of Photography* in this series). Zirconium, which ignites at low temperatures, is used in flash bulbs. The properties of stainless steel improve with the small additions of such metals as chromium, manganese, cobalt and nickel.

Many commonly used metals which fall into the previously called 'minor' group have not been mentioned here. You could research for yourself the contribution made by magnesium, cadmium, cobalt, mercury, radium, tantalum, tungsten and vanadium.

Word meanings

Alloy	A substance with metallic properties, composed of two or more elements, at least one of which is a metal.
Anneal	To soften a metal and return it to a more stable condition after working.
Brittleness	A measure of how easily a metal shatters on impact.
Casting	The product of a molten metal poured into a mold.
Corrosion	The deterioration of a metal by chemical reaction with its naturally-occurring surroundings.
Dislocation	An imperfection in the arrangements of the atoms in a grain.
Ductile	Able to be stretched without fracturing (a term usually applied to metals).
Eutectic mixture	An alloy composition which solidifies at one temperature rather than over a range of temperatures.
Fatigue	Resistance of a material to continuous alternating stresses.
Forging	A metal object shaped by mechanical means.
Galvanize	To coat iron with zinc to prevent it from rusting.
Grain	A region of metal where the atoms are aligned in a specific direction.
Grain boundary	The region of a metal between two atomic patterns arranged in different directions.
Hardness	Resistance of a metal to wear.
Miscible	Capable of being mixed (*with* something).
Ore	A naturally occurring combination mineral containing one or more metals which can be extracted.
Passivity	Lack of reactivity of a metal due to a protective coating applied to the metal.
Phase	A homogeneous region of a heterogeneous system with a definite boundary.
Phase (equilibrium) diagram	A graph showing the relationship between composition, temperature and structure for a system.
Pig iron (cast iron)	Iron containing more than 2 per cent carbon.
Quench	To cool a metal rapidly.
Steel	Iron containing less than 2 per cent carbon.
Temper	To relieve stresses formed during production.
Tensile strength	The highest load a metal can stand after gradual loading divided by its original area.
Wrought iron	Almost pure iron containing small amounts of intentionally added slag.

Reference materials

Books

Alexander, W. and Street, A. *Metals in the Service of Man*. London: Penguin, 1976.
Bailey, A.R. *Text Book of Metallurgy*. London: Macmillan, 1960.
Cottrell, A.H. *Theoretical Structural Metallurgy*. London: Edward Arnold, 1962.
Energy, Mines and Resources Canada, *Metal Mining in Canada, 1976-2000*. Ottawa, 1976.
Fisher, D.A. *Steel from the Iron Age to the Space Age*. New York: Harper and Row, 1967.
Jones, W.R. *Minerals in Industry*. London: Pelican, 1955.
Mander, M.R. and Pargeter, F.W.J. *Metals and Alloys*. London: Heinemann Educational Books, 1974.
Mining Association of Canada, *What Mining Means to Canada*. Ottawa, 1974.
Mining Association of Canada, *Mining in Canada: Facts and Figures*. Ottawa, 1976.
Parker, E.R., Davis, F.R. and Langer, E.L. *Solid State Structure and Reactions*. Ohio: American Society for Metals, 1969.
Rollason, E.C. *Metallurgy for Engineers*. London: Edward Arnold, 1961.
Unowski, J.S. *Ferrous Metallurgy – Lab Manual*. Chicago: American Technical Society, 1960.
Various authors, "Materials", *Scientific American*, September, 1967.
Wohlrabe, R.A. *Metals*. Philadelphia: J.B. Lippincott, 1964.

Films

A wide range of films are available from The Steel Company of Canada Ltd., Audio Visual Services, Stelco Tower, King Street West, Hamilton, Ontario, L8N 3T1.
The following INCO films are available from Association Films, 333 Adelaide Street West, Toronto, Ontario, M5V 1R6:
"Corrosion in Action". 16 mm, colour, 44 min.
"Developing a Natural Resource: Mining for Nickel". 16 mm, colour, 35 min.
"The Winning of Nickel". 16 mm, colour, 33 min.

Filmstrips and slides

"The Chemistry of Iron", "The Chemistry of Steel" and "Raw Materials of Steel Making". American Iron and Steel Institute, 100 Sixteenth Street, N.W., Washington, D.C., 20036.
"The Chemistry of Aluminum". Aluminum Company of Canada Ltd., Public Affairs Department, P.O. Box 6090, Montreal, Quebec, H3C 3H2.

Pamphlets

Most of the above organizations also have many pamphlets available on request.

Special materials for experiments

This list is of special materials not normally stocked in a school laboratory, but which would be needed for a class of thirty students to complete all the experiments in this book.

Chapter 1
Cresol (5 cm^3)
Sodium or potassium ethyl xanthate (5 g)
Vacuum cleaner
Paint stirrer

Chapter 2
10 metal strips, about 10 cm long, of each of: iron, steel, stainless steel, Mumetal, copper, bronze, brass, silver, EPNS, lead, tin, solder, galvanized iron.
Masonry drills (10)
2-naphthol (100 g)
1-naphthol (100 g)
15 pieces of 0.1, 0.4, 1.2 per cent steel
Metallurgical microscope (or adapted biological microscope)
Metal polish (5 tins)

Chapter 3
30 steel hairpins
Tensile machine
Fluorescein (100 cm^3)
Ultra-violet lamp
Steel forgings (15) (off-cuts from the local machine shop)
Photographic paper (100 sheets)

Chapter 4
Ammonium thiocyanate (25 g)
30 stainless steel strips, about 20 cm long
Potassium ferricyanide (25 g)

SI units conversion chart

SI UNITS				
	Name	SI unit	Derived SI unit	Equivalent
Length	Kilometre	—	1 km	0.621 mile
	Metre	1 m	—	3.28 ft
	Centimetre	—	1 cm	0.394 in
Area	Square metre	$1\ m^2$	—	$10.76\ ft^2$
	Hectare	—	1 ha	2.47 acres
Volume	Cubic metre	$1\ m^3$	—	$35.3\ ft^3$
	Cubic centimetre	—	$1\ cm^3$	$0.061\ in^3$
	Litre (= $1000\ cm^3$)	—	1 L	1.050qt
Mass	Kilogram	1 kg	—	2.205 lb
	Gram	—	1 g	0.035 oz
Energy	Joule	1 J	—	0.238 cal
Pressure	Pascal	1 Pa	—	$0.000\ 145\ lb/in^2$
	Megapascal	—	1 MPa	9.87 atm
Time	Second	1 s	—	1 sec

Index

Activity series 36
Alchemists vii
Alloy, definition 16, 43
, comparison tests, alloys and pure metals 16
, non-ferrous alloys, composition and uses 18
α (alpha) iron: body-centred cubic 28
Aluminum, discovery 14
, concentration 15
, uses 15
Annealing of steel 30
Antimony, discovery vii
, phase diagram, lead-antimony system 23
Arsenic, discovery vii
Austenite 28

Basic oxygen furnace (BOF) 8
Bauxite, sources 14
, chemical composition 14
, refining 14, 15
Beryllium 40
Bessemer, Henry 6
Bessemer converter 6, 7
Bismuth, discovery vii
Blast furnace viii, 5
Blister copper 12
Body-centred cubic (b.c.c.) 27
BOF (basic oxygen furnace) 8
Boron 42
Brittleness test (impact) 16
Bronze, discovery vi
, importance vi
, modern use 18
Bubble raft 31, 32

Cesium 42
Cast iron viii, 5
Catalan forge viii
Cementite 28-30
Charcoal, in iron refining vi, viii
Charpy or Izod test 30
Civilization, characteristics vi
Coke, in iron refining viii, 5
Copper, Canadian production 2, 10
Corrosion, in cars 35
, in bridges 36
, prevention 36
Corrosion testing 16

DeHavilland Dash 7 39
δ (delta) iron: body-centred cubic 28
Deformation, elastic 30
, plastic 30
Dislocation 31
Distillation vii, 14
Ductility 33

Electric arc furnace 8
Electrolytic refining, laboratory experiment 4
, of aluminum 15

Electrolytic refining, (continued)
, of copper 12, 13
Etching of metal samples 27, 29
Eutectic mixtures 22

Face-centred cubic (f.c.c.) 27, 28
Fatigue test 16
Ferrite 28-30
Flotation cell, origin 10
, model 11
, in industry 12, 13
Fluorescent test for cracks 34
Flux, used in reduction 4
Freezing point, definition 20

Galena (PbS) 10, 13
Galvanizing 14, 36
γ (gamma) iron: face-centred cubic 28
Gardiner Expressway, anti-corrosion measures 36
Gold, early discovery and use v

Hafnium 42
Hardness test 16
Heat treatment of steel 30
Hume-Rothery, W. 17

Inconel 625 40
Industrial Revolution viii
Immiscible alloys 17
Impact test 16, 30
Iron, early working vi
, cast (pig) iron viii, 5
Iron ore, Canadian sources 4
, refining 5
Izod or Charpy test 30

Lead, Roman use vi
, phase diagram of lead-tin system 24, 25
, phase diagram of lead-antimony system 22, 23
, refining 13, 14
Liquidus 20
Lithium 42

Magnetic dust test for cracks in metals 34
Magnetism test 16
Martensite 30
Melting point, definition 20
Mercury, Roman use vi
Metallurgy, definition v
Metallurgical microscope 26, 27
Microstructure, of lead-tin alloys 26, 27
, of carbon steel 29,
Mineral production, Canadian 1, 2, 4, 10
Miscible alloys 17
Molyslip (molybdenum disulphide) 42

Naphthalene 19, 20, 22
1-naphthol 22
2-naphthol 20
Neolithic (New Stone) Age v
Nickel, Canadian production 13
, phase diagram of copper-nickel system 21
, uses 13, 18, 36
Niobium (columbium) 42

Open-hearth furnace 7
Ores, definition 1, 43

Palladium 41
Pearlite 28
Pentlandite 13
Phase, definition of 17, 43
Phase diagrams 19-28
Pig (cast) iron 5, 43
Platinum 41

Reduction, of an oxide with hydrogen 3
, of an oxide with carbon 4

Semi-conductors 42
Silicon 18, 42
Silver, early discovery and use v
, modern uses, 42
Silverthorne Collegiate 36
Slag, and blast furnace 4, 5
Smelting, discovery v, vi
Solid solutions, substitutional and interstitial 17
Solidus 20
Steel, definition 6, 43
, basic oxygen furnace 8
, Bessemer converter 6
, electric arc furnace 8
, iron-carbon system 27-30
, open-hearth furnace 7
Stelcoloy (weathering steel) 36
Strength (tensile) testing 33
Stress 30, 31
Sulphur dioxide 13
Sulphur print test 34

Tempering 30
Tensile testing 33
Tin, alloyed with copper vi, viii, 18
, phase diagrams for tin-lead system 24, 25
Titanium 39, 40

Uranium 41

Whiskers, metal 42
Work-hardening 32
Wrought iron 43

Zinc, Roman use vi
, modern use 14, 18, 36
, refining 14
Zinc blende (ZnS) 13
Zirconium 18, 42

BOOK SOCIETY OF CANADA

B40026

ISBN-0-7725-2005-4